



Variations in FASST Predictions of Soil Surface Temperatures

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Abstract: This report presents the results of a systematic investigation of the variation in soil surface temperatures predicted by the numerical model FASST (Fast All Seasons Soil Strength), using different values of soil physical, thermal, and optical parameters. Soil hydraulic properties were not varied. Single-factor experiments have shown that the major soil parameters for FASST predictions are, in descending order, initial volumetric soil moisture content, bulk density of the dry soil material, albedo (sunny days), and porosity. The thermal conductivity of the dry soil material has a minor effect on predicted soil temperature. Quartz content, specific heat of the dry soil material, and emissivity each has a negligible effect on predicted soil temperature. Experiments varying several soil parameters simultaneously produced temperature differences (relative to a standard soil) for some combinations of factors that are larger than were obtained by varying a single major soil factor. This highlights the difficulty of associating a measure of confidence with a given FASST simulation, i.e., how closely predicted temperatures will match actual soil temperatures for a given soil type and weather scenario, given that the predicted temperature depends on the cumulative effect of the accuracy of the value assigned to each of the significant soil parameters.

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Preface

This report was prepared by Dr. Lindamae Peck, Geophysical Sciences Branch, Cold Regions Research and Engineering Laboratory (CRREL), U.S. Army Engineer Research and Development Center (ERDC), Hanover, NH.

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The report was prepared under the general supervision of Janet Hardy, Acting Chief, Geophysical Sciences Branch; Dr. Lance Hansen, Deputy Director; and James L. Wuebben, Acting Director, CRREL.

The Commander and Executive Director of the Engineering Research and Development Center is COL James R. Rowan. The Director is Dr. James R. Houston.

1 Introduction

FASST (Fast All Seasons Soil STrength) is a numerical model for predicting soil temperature and moisture content. State-of-the-ground deductions, including whether the ground is unfrozen, frozen, or thawing, its wetness, and snow cover development and persistence, are derived from FASST simulations of soil temperature and moisture profiles and used by U.S. Army Battlefield Terrain Reasoning and Awareness (BTRA) products to generate guidance on expected troop mobility, military engineering tasks, and battlefield sensor performance. The effectiveness of BTRA guidance depends on the agreement between FASST predictions and the actual temperatures and moisture contents of soils in the area of interest, which in turn depends on how well a soil is represented by the physical, optical, and thermal properties selected to characterize it in FASST simulations.

This report presents the results of a systematic investigation of the variation in soil surface temperatures predicted by FASST, using different values of soil physical, thermal, and optical parameters. [The influence of soil hydraulic properties (saturated hydraulic conductivity and water retention parameters) on predicted surface temperatures is the subject of another study.] The soil factors investigated here are moisture content, dry bulk density, porosity, quartz content, thermal conductivity of dry soil material, specific heat of dry soil material, emissivity, and albedo. For these eight soil factors, three levels of effect (low, medium, and high values of each parameter, determined from the range in published values of a factor) are investigated both individually and in two series of four soil factors each. For the latter sensitivity studies, the nine combinations of levels used are determined by a Greco-Latin square experiment design for four factors with three levels and negligible or no interactions between factors (Appendix A). The resulting nine experiments for each of two series of factors and two soil types under two weather scenarios result in a total of seventy-two FASST simulations. Sixteen additional FASST simulations, all with the same soil type and the same weather scenario, investigate the effect on predicted soil temperature of varying a single soil factor at a time.

2 Virtual operating environment

Soil types

Any soil type might have been selected, since the purpose of this study was to quantify the change in predicted soil temperature caused by varying one or more soil parameters by known amounts, rather than to compare predicted and measured temperatures for an actual soil. That is, soil type was not constrained by the availability of both measured temperatures and meteorological data required to run FASST. Loam was initially selected as the test soil type because it is a “middle-of-the-road” soil type: low clay content, moderate sand content, and high silt content. Subsequently silt and silt loam were included to broadly represent fine-grained (non-clay) soil. Upon consideration that misidentifying a non-clayey soil as loamy would underrepresent its quartz content, which in turn would affect the suitability of calculated or default soil thermal properties, a second group of three soils with higher quartz content—loamy sand, sandy loam, and sandy clay loam—was selected to broadly represent coarse-grained (non-gravel) soil.

Loam, silt, silt loam, loamy sand, sandy loam, and sandy clay loam are U.S. Department of Agriculture soil textures. A compilation of soil properties (Appendix B) lists soil hydraulic and physical properties by USDA soil textural classes, which are based on composition (percentages of sand, silt, and clay). When considering thermal properties or engineering parameters, soils are more commonly designated in accordance with the Unified Soil Classification Scheme (USCS). These two schemes reflect the different soil characteristics relevant to their primary users, i.e., soil scientists concerned with water infiltration and moisture retention versus engineers concerned with load bearing and deformation.

According to a proposed correspondence between the USDA soil textural triangle and the USCS soil designations (Appendix B), the soil grouping of loam, silt, and silt loam corresponds to USCS soil type MH, and the soil grouping of loamy sand, sandy loam, and sandy clay loam corresponds to USCS soil type SM. For conciseness, the two composite soils used in this study are referred to as MH and SM.

A reference MH soil and a reference SM soil for FASST simulations are defined using medium values of each soil parameter (soil factor). The

exception is moisture content, for which low moisture content is the reference condition. These two soils are described below under “Standard soils” in the section “Variation in soil parameters.”

Weather

Two weather scenarios were created for evaluating the variation in predicted soil surface temperature with soil properties. Each is 72 hours long (hourly time increment) and consists of a 24-hour-long actual weather record from the SOROIDS meteorological database followed by two repetitions. (SOROIDS, or South Royalton Intrusion Detection Systems, is a former CRREL sensor system test site in Vermont.) The “sunny” scenario is based on the weather of 26 June 1991; the “cloudy” scenario is based on the rainy weather of 13 July 1991, except that the rainfall amount is set to zero throughout the scenario. The “sunny” and “cloudy” scenarios are primarily distinguished by differences in incident solar radiation (Fig. 1) and air temperature (Fig. 2).

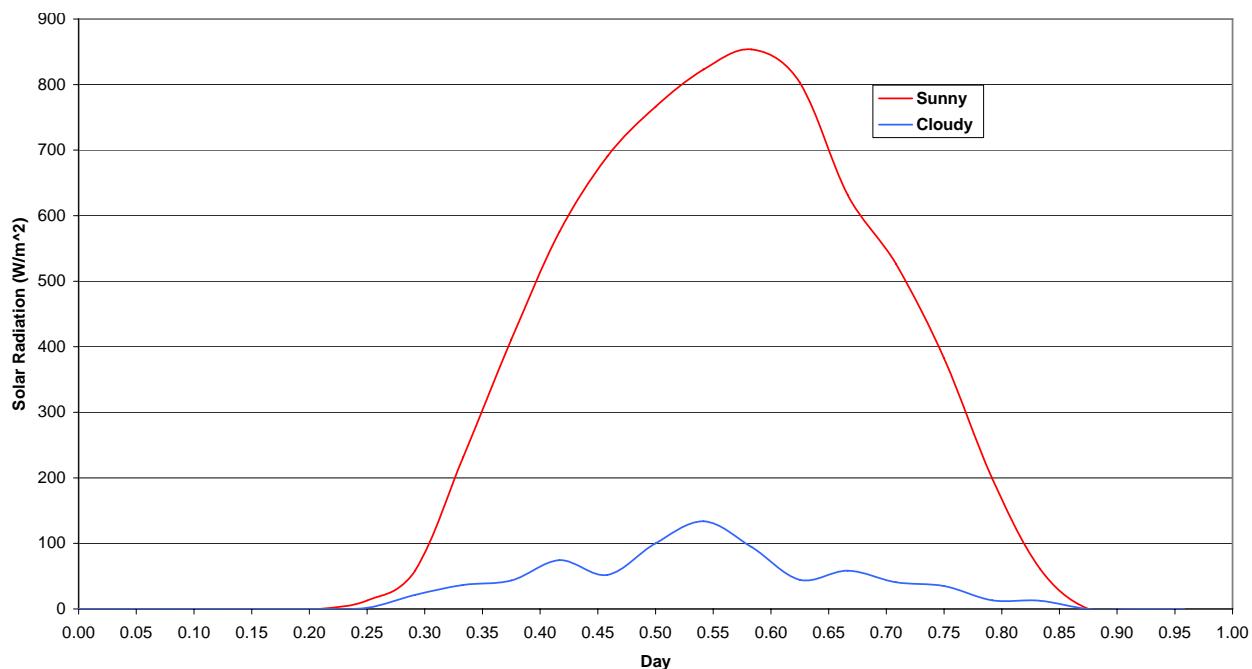


Figure 1. Measured incident solar radiation at SOROIDS, 26 June 1991 (sunny scenario) and 13 July 1992 (cloudy scenario).

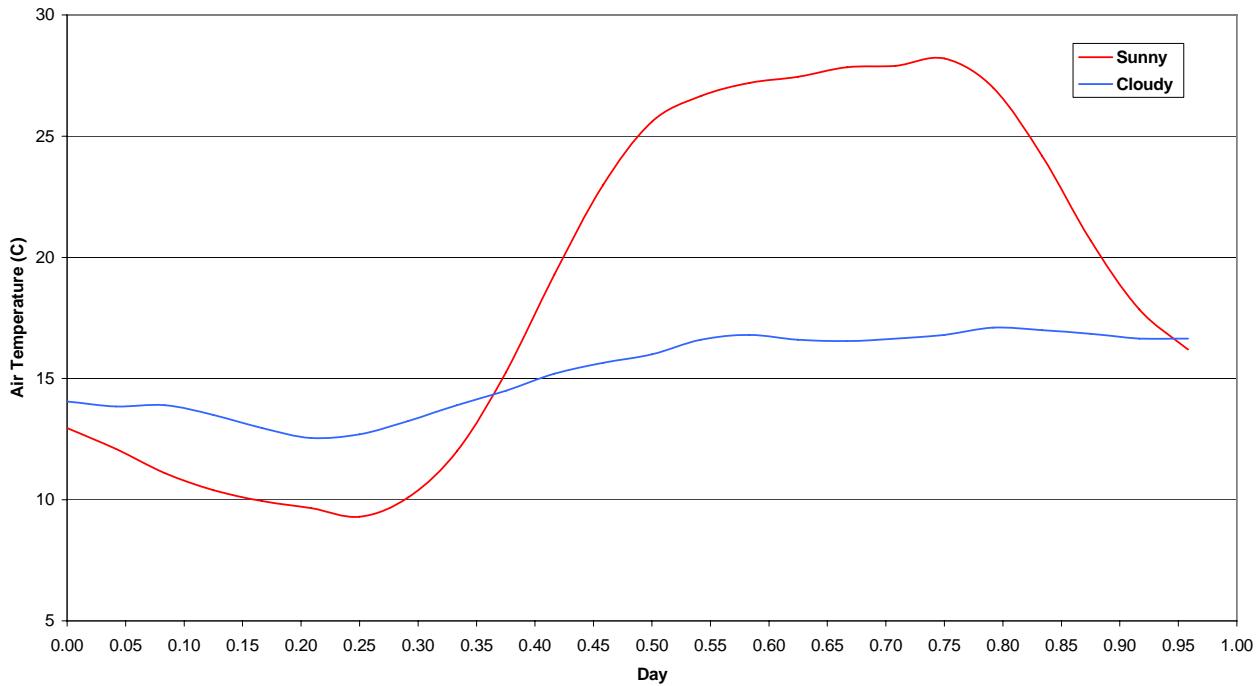


Figure 2. Measured air temperature at SORODS, 26 June 1991 (sunny scenario) and 13 July 1991 (cloudy scenario).

Initial soil temperatures

Two different soil temperature profiles were used to initialize FASST (Table 1), depending on whether the sunny or the cloudy weather scenario was being run. The temperature profiles are based on thermocouple measurements to a depth of 60 cm at SORODS on 26 June 1991 and 13 July 1991. The 17-day difference in when the measurements were made accounts for the slightly higher soil temperatures associated with the cloudy weather scenario.

Table 1. Initial soil temperature (°C) profiles for sunny and cloudy weather scenarios.

Depth (cm)	Sunny scenario	Cloudy scenario
0	15.0	16.5
7.5	20.0	21.0
15.0	19.5	20.0
22.5	19.0	19.0
30.0	18.5	19.0
37.5	18.0	18.0
45.0	17.0	18.0
52.5	16.0	17.0
60.0	16.0	17.0

Initial soil moisture content

The effect of soil moisture on predicted surface temperature was investigated by varying the moisture content profile used to initialize each soil. Volumetric soil moisture content at a given depth was set at 11, 17.5, or 21%; how these values were obtained is explained below under “Moisture content” in the section “Variation in soil parameters.” The initial moisture content was specified at nine soil depths from the surface (0 cm) down to 60 cm (Table 2). For the low moisture content cases, the entire soil profile is designated as dry (11% volumetric moisture content). For the medium (17.5%) and wet (21%) moisture contents, wetter soil overlies dryer soil. For MH soil, the moist surface layer extends to 30 cm; for SM soil, the moist surface layer extends to 60 cm. The thickness of the moist surface layer is based on the lower boundary of soil moisture control sections reported by the Soil Survey Staff (1999) for soil particle-size classes that include fine-loamy, coarse-silty, and fine-silty soils (MH soil in this study) or coarse-loamy soil (SM in this study). The lower boundary marks how deep a dry soil would be moistened by 7.5 cm of rain in 48 hours (Appendix B).

Table 2. Initial soil moisture content (volume %) profiles for MH and SM soils.

Depth (cm)	MH dry	MH medium	MH wet	SM dry	SM medium	SM wet
0	11.0	17.5	21.0	11.0	17.5	21.0
7.5	11.0	17.5	21.0	11.0	17.5	21.0
15.0	11.0	17.5	21.0	11.0	17.5	21.0
22.5	11.0	17.5	21.0	11.0	17.5	21.0
30.0	11.0	11.0	11.0	11.0	17.5	21.0
37.5	11.0	11.0	11.0	11.0	17.5	21.0
45.0	11.0	11.0	11.0	11.0	17.5	21.0
52.5	11.0	11.0	11.0	11.0	17.5	21.0
60.0	11.0	11.0	11.0	11.0	11.0	11.0

Variation in the moisture profile is slight over the 72-hour simulations, none of which incorporated rainfall as a source of water to infiltrate the soil. With the MH soils, for example (Table 3), moisture change over 72 hours is greater with the sunny weather scenario than under cloudy conditions, which intuitively is consistent with daytime evaporational loss. The sunny scenario also resulted in more variability in the change in surficial soil moisture among the simulations (indicated by the ranges in column 4), which highlights the influence of other soil parameters (both physical and thermal) on moisture loss due to heating of the soil surface.

Table 3. Change in surface moisture of MH soils by the completion of a 72-hour simulation. The initial moisture contents are shown in Table 2.

Soil moisture content	Weather scenario	Surface moisture content after 72 hours (%)	Change in surface moisture content over 72 hours (%)
Dry	Sunny	10.3–10.5	0.5–0.7
Dry	Cloudy	11.0	0
Medium	Sunny	16.6–16.8	0.7–0.9
Medium	Cloudy	17.4	0.1
Wet	Sunny	20.1–20.3	0.7–0.9
Wet	Cloudy	20.7–20.9	0.1–0.3

Reference plots

Preliminary FASST simulations were done to assess the suitability of the virtual soils (MH and SM) and the virtual weather (sunny and cloudy scenarios) developed for this study. Model output was presented as reference plots, i.e., time-series records of predicted soil surface temperatures. The criteria applied were the reasonableness of predicted soil surface temperatures under sunny and cloudy conditions, the magnitudes of diurnal variability in soil temperature, and the differences in surface temperature with soil type. Model results also were assessed for physical realism in terms of expected variation in soil temperature with moisture content.

Predicted surface temperatures of the standard soils for the sunny and cloudy weather scenarios and the three moisture states (11, 17.5, and 21 volume % moisture) are shown in Figures 3 and 4 and summarized in Table 4. Under sunny daytime conditions, the MH soil surface is predicted to be warmer than the SM soil surface by a few degrees; the temperature difference due to soil type is much less under cloudy conditions. Both soils are warmer during the day and colder at night under the sunny weather conditions. This stronger diurnal temperature cycle under the sunny scenario results from greater daytime solar heating (higher insolation) and greater nighttime radiational cooling (absence of cloud cover). For a given weather scenario, dry soil experiences higher daytime and lower nighttime surface temperatures. This is because the lower thermal conductivity associated with drier soil results in less transfer of heat from the hot surface to cooler soil at depth during the daytime solar loading and, conversely, less transfer of heat from the interior of the soil layer toward the cooler surface while nighttime radiational cooling is occurring.

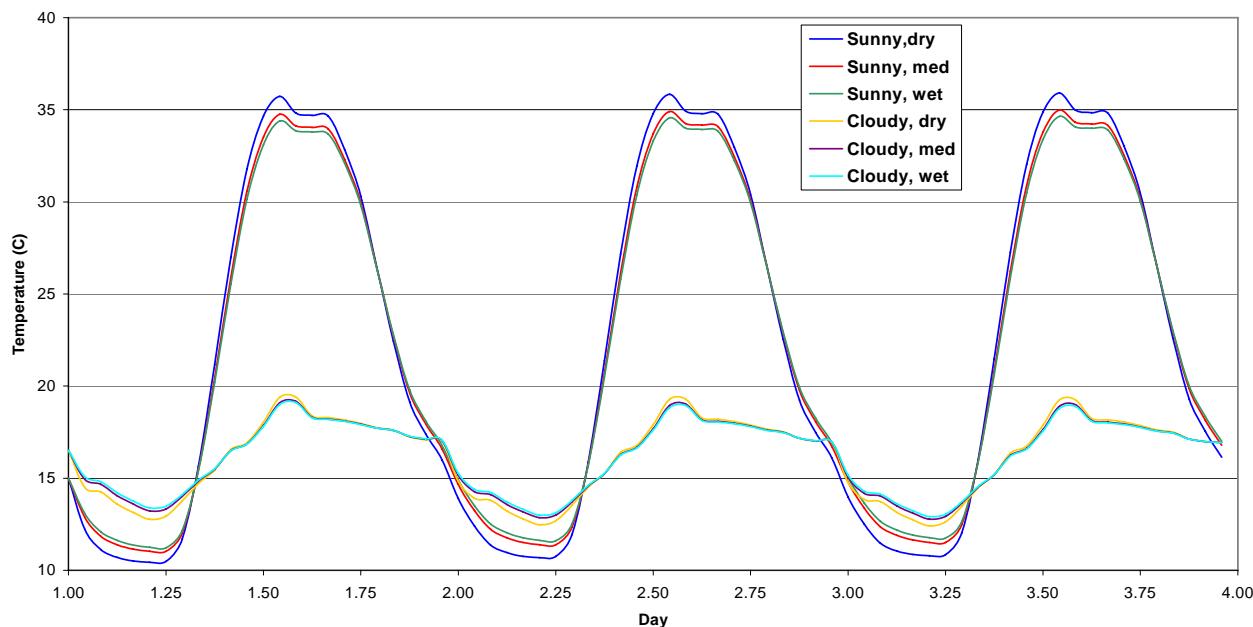


Figure 3. Predicted surface temperatures of standard MH soil (Series 1 soil parameters) under sunny and cloudy weather scenarios for dry, medium, and wet moisture states. The standard MH soil is defined using medium values of the other soil parameters (soil factors).

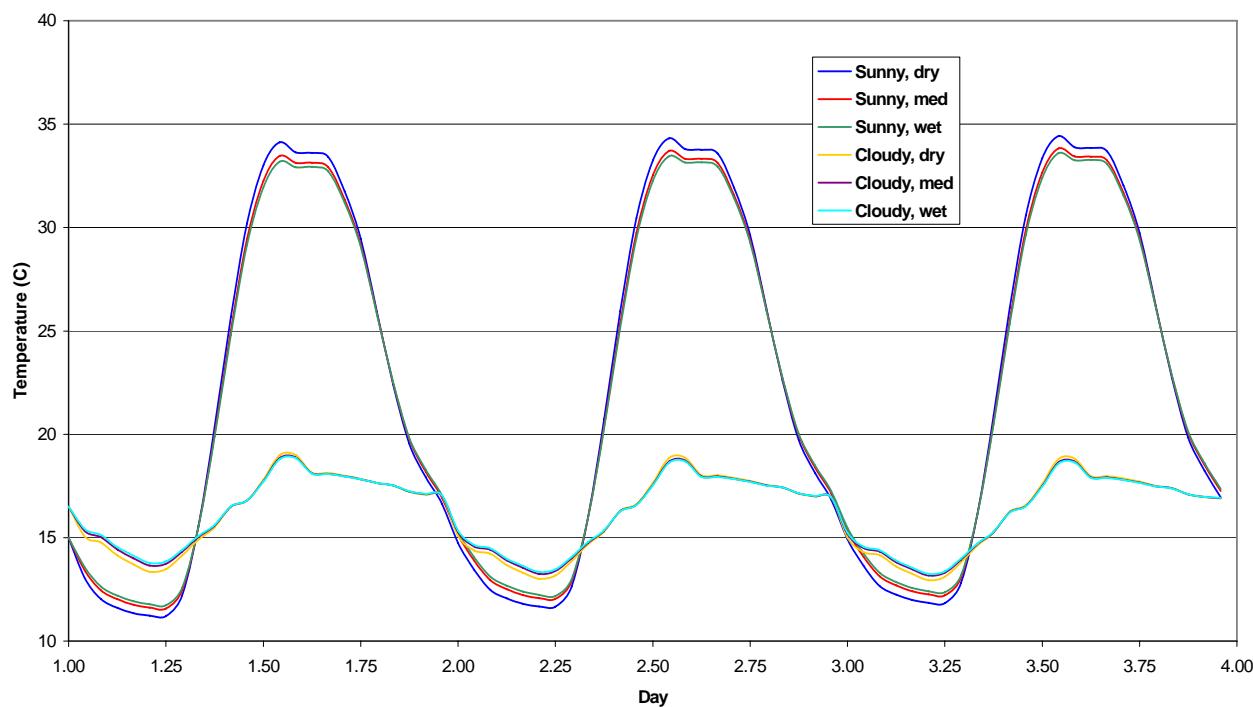


Figure 4. Predicted surface temperatures of standard SM soil (Series 1 soil parameters) under sunny and cloudy weather scenarios for dry, medium, and wet moisture states. The standard SM soil is defined using medium values of the other soil parameters (soil factors).

Table 4. Diurnal maxima and minima of predicted soil surface temperatures that are plotted in Figures 3 and 4. Maximum temperature for each soil corresponds to approximately noon on day 3 (approximately 3.5 on the time scale). Minimum temperature corresponds to approximately 0600 hours on day 3 (approximately 3.25 on the time scale). Dry, medium, and wet refer to the initial soil moisture as defined by the profiles given in Table 2.

Soil	Sunny scenario			Cloudy scenario		
	Maximum temperature (°C)	Minimum temperature (°C)	Diurnal temperature range (°C)	Maximum temperature (°C)	Minimum temperature (°C)	Diurnal temperature range (°C)
MHS1 dry	35.91	10.79	25.12	19.25	12.42	6.84
MHS1 medium	34.98	11.51	23.48	18.98	12.78	6.20
MHS1 wet	34.64	11.75	22.89	18.89	12.92	5.98
SMS1 dry	34.42	11.84	22.58	18.82	12.94	5.88
SMS1 medium	33.83	12.22	21.61	18.69	13.17	5.52
SMS1 wet	33.60	12.36	21.24	18.64	13.26	5.38

Although neither the MH soil nor the SM soil was optimized to be a good match to the loamy soil at SOROIDS, it is informative to compare predicted soil surface temperatures with those measured with a thermo-couple located roughly at the thatch/soil interface at SOROIDS. On 26 June 1991 (which corresponds to the sunny weather scenario), the maximum measured soil surface temperature was approximately 43°C; on 13 July 1991 (which corresponds to the cloudy weather scenario), the maximum measured soil surface temperature was approximately 18°C.

FASST calculates the thermal conductivity, κ , of non-peat soils from $\kappa = (\kappa_{sat} - \kappa_{dry}) K_e + \kappa_{dry}$, where K_e is the Kersten number, in accordance with Johanson (1975). The thermal conductivity of dry soil, κ_{dry} , is either specified by the user or calculated from the dry density of the soil (either specified by the user or using a default value for that soil type). The temperature-dependent thermal conductivity of saturated soil, κ_{sat} , is calculated from the soil porosity, the thermal conductivity of the soil solids (κ_s), and both the unfrozen and frozen moisture contents of the soil. The thermal conductivity of the soil solids is calculated from the soil's quartz content and organic fraction and depends on grain size (fine vs. coarse soil). Either the user provides the soil parameters needed to calculate κ_{sat} and κ_s as model inputs or FASST utilizes default values of dry density,

porosity, quartz content, organic fraction, and coarseness based on soil type specified by the user. In general terms, the thermal conductivity of dry soil is greater the less porous the soil is, and the thermal conductivity of naturally wet soil increases with moisture content. The latter effect is evident in Figures 3 and 4 and Table 4, with MHS1 and SMS1 each having the greatest diurnal range in temperature when dry.

3 Variation in soil parameters

Experiment design

The dependence of predicted soil surface temperature on the values of soil physical, thermal, and optical parameters was investigated by varying parameters independently (one by one) and in combination. The latter simulations are designated Series 1 and Series 2. Series 1 varied the values assigned to water content, albedo, and thermal conductivity and bulk density of the dry soil material. Series 2 varied the values assigned to porosity, quartz content, emissivity, and specific heat of the dry soil material. In all cases the intrinsic density of the MH and SM soils was assumed to be 2.7 g/cm³, and each soil's hydraulic properties were mostly the default values assigned within FASST (Frankenstein and Koenig 2004, Tables 9.2.1 and 9.2.2). The exception to using the default values is that the maximum water content (volume %) of this study's MH and SM soils was set equal to the soil's porosity under each simulation.

With Series 1, specifying a soil's dry bulk density determined the soil's volume fraction of solids, porosity, and void ratio, as indicated under the dependent soil parameters section in Table 5; the appropriate values of the dependent parameters were included in the soil input file. For Series 2, the soil porosity was specified, and the dry bulk density and volume fraction of solids were designated as unknown (999.0).

Table 5. Values of soil parameters used in the sensitivity study. The initial moisture content of the soil surface is listed here; the initial soil moisture profiles are presented in Table 2.

Series 1 Experiments				
Thermal conductivity, K_{dry} (W/m·°C)				
Soil	Range	K_{dry} low	K_{dry} medium	K_{dry} high
MH	0.25–0.37	0.27	0.31	0.36
SM	0.29–0.83	0.36	0.56	0.76
Moisture content, ww (vol/vol)				
Soil	Range	ww_{low}	ww_{medium}	ww_{high}
MH	–	11.0	17.5	21.0
SM	–	11.0	17.5	21.0

Table 5 (cont.).

Albedo, α [dry soil]				
Soil	Range	α low	α medium	α high
MH	0.15–0.35	0.175	0.250	0.325
SM	0.15–0.35	0.175	0.250	0.325
Bulk density of dry soil, γ_d (g/cm ³)				
Soil	Range	γ_d low	γ_d medium	γ_d high
MH	1.01–1.62	1.09	1.32	1.54
SM	1.20–1.75	1.27	1.48	1.68
Series 1 Dependent Parameters				
Volume fraction of solids, θ_d = [bulk density of dry soil] / [intrinsic density of dry soil (2.7 g/cm ³)]				
Soil	Range	θ_d^*	θ_d^\dagger	θ_d^{**}
MH	–	0.404	0.489	0.570
SM	–	0.470	0.548	0.622
Porosity, $n = 1 - (\text{volume fraction of solids})$				
Soil		n^*	n^\dagger	n^{**}
MH	–	0.596	0.511	0.430
SM	–	0.530	0.452	0.378
Void Ratio, $e = (\text{Porosity}) / (1 - \text{porosity})$				
Soil		e^*	e^\dagger	e^{**}
MH	---	(set to 1.0)	(set to 1.0)	0.754
SM	---	(set to 1.0)	0.825	0.608
Series 2 Experiments				
Porosity, n				
Soil	Range	n_{low}	n_{medium}	n_{high}
MH	0.375–0.582	0.401	0.479	0.556
SM	0.332–0.555	0.360	0.444	0.527

*Derived from low value of bulk density.

† Derived from medium value of bulk density.

** Derived from high value of bulk density.

Table 5 (cont.).

Quartz Content, q				
Soil	Range	q_{low}	q_{medium}	q_{high}
MH	0.36–0.51	0.38	0.44	0.49
SM	0.49–0.70	0.52	0.60	0.67
Specific Heat, C (J/kg·°C)				
Soil	Range	C_{low}	C_{medium}	C_{high}
MH	808.1–875.0	816.5	841.6	866.6
SM	808.1–824.8	810.2	816.5	822.7
Emissivity, ϵ				
Soil	Range	ϵ_{low}	ϵ_{medium}	ϵ_{high}
MH	–	0.93	0.97	0.99
SM	–	0.93	0.97	0.99
Series 2 Dependent Parameters				
Void Ratio, $e = (\text{Porosity}) / (1 - \text{Porosity})$				
Soil	Range	e^*	e^{\dagger}	e^{**}
MH	–	0.669	0.919	(set to 1.0)
SM	–	0.563	0.799	(set to 1.0)

*Derived from low value of porosity.

† Derived from medium value of porosity.

** Derived from high value of porosity.

Three levels of effect were investigated for each of the eight soil factors (dry thermal conductivity, moisture content, albedo, dry bulk density, porosity, quartz content, dry specific heat, and emissivity). They represent high, medium, and low values of the factor. The procedure for determining the values for each level is presented here, using thermal conductivity as an example.

1. The range in thermal conductivity of a given soil type is $R = \kappa_2 - \kappa_1$ (W/m·°C), where $\kappa_1 < \kappa_2$ and κ_1 (κ_2) is the lowest (highest) reported thermal conductivity for a soil.
2. $R/8$ establishes the size of this soil's thermal conductivity "bin."
3. Nine discrete thermal conductivity values are determined as shown in Table 6, with three each in the low, medium, and high categories.
4. The middle value is selected from each of the three categories and is referred to as that soil type's representative low, medium, or high thermal conductivity level.

Table 6. Relationship between three levels of a given factor (e.g., thermal conductivity) and the range of values of that factor for a given soil type.

Thermal conductivity value	Thermal conductivity category	Thermal conductivity level
K_1	Low	
$K_1 + (R/8)$	Low	Low
$K_1 + [2 \times (R/8)]$	Low	
$K_1 + [3 \times (R/8)]$	Medium	
$K_1 + [4 \times (R/8)]$	Medium	Medium
$K_1 + [5 \times (R/8)]$	Medium	
$K_1 + [6 \times (R/8)]$	High	
$K_1 + [7 \times (R/8)]$	High	High
$K_1 + [8 \times (R/8)]$, or K_2	High	

Standard soils

Two standard soils, one each for MH and SM, were defined to provide a reference for assessing the significance of the various factors in predicting soil surface temperature. The standard soils were assigned medium values of dry thermal conductivity, albedo, quartz content, emissivity, and dry specific heat. For Series 1 experiments, the standard soils also were assigned medium values of dry bulk density, which in turn determined the values of volume fraction of solids and porosity that were input; for Series 2 experiments, the standard soils were assigned medium values of porosity, and dry bulk density and volume fraction of solids were designated as unknown (999.0). For both series of experiments, the standard soils were assigned a low moisture content.

Defining the standard soils as being “medium” in terms of their soil physical, thermal, and optical properties and dry with respect to moisture content was done in anticipation that such a combination of parameter values may be a common choice among FASST users. That is, when soil characterization (other than soil type) is unavailable or incomplete, a user of FASST might be inclined to input mid-range values of the required soil parameters as a “safe” approximation. The exception is moisture content, for which an assumption of dry soil was considered to be more general.

Thermal conductivity of the dry soil

The range in thermal conductivity ($\text{W}/\text{m} \cdot ^\circ\text{C}$) of dry MH and SM soils is based on measurements of thermal conductivity of soils at 0% moisture reported by Salomone and Marlowe (1989) and reproduced in Table B17 (Appendix B). Salomone and Marlowe listed the thermal conductivity (0% soil moisture) of twelve SM soils, which define a range of 0.29–0.83 $\text{W}/\text{m} \cdot ^\circ\text{C}$ for the SM soil. They did not provide data for MH soils, so as a substitute, their data for eleven ML soils were used, which gives a range of 0.25–0.37 $\text{W}/\text{m} \cdot ^\circ\text{C}$. Soil types ML and MH are both fine-grained soils and include silts and fine sandy or silty soils; their different liquid limits and levels of plasticity, caused largely by the inclusion of soils with more clay content in the ML class, is the main distinction between them. Applying the process described under “Experimental design” results in the low, medium, and high values of thermal conductivity of dry soil listed in Table 5.

Moisture content

The range in moisture content for the MH and SM soils is based on the maximum and minimum volumetric moisture contents (%) of loamy sand in dry, moderate, and wet climates, as reported by Miller et al. (1992) and reproduced in Table B2 (Appendix B). In dry climates (<20 in./yr rainfall), the volumetric moisture content of loamy sand is 5–17%; a value of 11% was selected for low-moisture-content simulations with FASST. In moderate climates (20–80 in./yr rainfall), the moisture content of loamy sand is 10–25%; 17.5% was selected for medium-moisture-content FASST simulations. In wet climates (>80 in./yr), the moisture content of loamy sand is 15–27%; 21% was selected for high-moisture-content FASST simulations.

Albedo

Low, medium, and high values of the albedo of the MH and SM soils are derived from Wilson (1984), as reproduced in Table B12 (Appendix B). Wilson reported typical soil albedos for light, medium, and dark soil color classes and for wet and dry soils. For this study, the variation in albedo with soil color provides a useful range of values, which is 0.07–0.18 for wet soil and 0.15–0.35 for dry soil. It was decided to use a “dry soil” albedo in all cases, even when the moisture content of the soil was initialized at medium or high levels. In the absence of rainfall, and especially under a sunny weather scenario, it is realistic for the soil surface to be dry, regardless of how moist the interior of the soil layer is. Applying the process

described under “Experimental design” results in the low, medium, and high values of albedo listed in Table 5.

Dry bulk density

Low, medium, and high values of dry bulk density of the MH and SM soils are based on the ALL database of soils reported by Schaap and Leij (1998) and reproduced in Table B7 (Appendix B). Although Schaap and Leij did not explicitly state that the bulk densities they listed are for dry soil, a cross-check with dry bulk densities reported by Steinmanis (1989) and Salomone and Marlowe (1989) (reproduced in Table B8, Appendix B) shows that the Schaap and Leij bulk densities are less than or comparable to the known dry bulk densities.

For this study, the range in dry bulk density is taken to be 1.01–1.62 g/cm³ for MH soil and 1.20–1.75 g/cm³ for SM soil (Table 7). Applying the process described under “Experimental design” results in the low, medium, and high values of dry bulk density listed in Table 5. For Series 1 experiments, defining dry bulk density in turn defined the input values of volume fraction of solids, porosity, and void ratio.

Table 7. Selected bulk densities of soils in the ALL database. (From Schaap and Leij 1998.)

Soil type (this study)	USDA soil classes of ALL database	Bulk density, mean (g/cm ³)	Bulk density, standard deviation (g/cm ³)	Range (mean ± one standard deviation)
MH	Loam	1.37	0.25	1.12–1.62
	Silty loam	1.28	0.27	1.01–1.55
	Silt	1.33	0.09	1.24–1.42
SM	Loamy sand	1.52	0.19	1.33–1.71
	Sandy loam	1.46	0.26	1.20–1.72
	Sandy clay loam	1.57	0.18	1.39–1.75

Porosity

Low, medium, and high values of porosity of the MH and SM soils are derived from the listing of total soil porosity by USDA soil type from Rawls et al. (1982, 1992), which is reproduced in Table B9 (Appendix B). Table 8 shows the porosity data used to define the porosity of the MH and SM soils of this study for Series 2 experiments. The range in porosity is taken to be 0.375–0.582 for MH soil and 0.332–0.555 for SM soil. Applying the process described under “Experimental design” results in the low, medium, and high values of porosity listed in Table 5 under Series 2 experiments.

Table 8. Selected total porosity of soils. (From Rawls et al. 1982, 1992.)

Soil type (this study)	USDA soil classes	Total porosity, mean (cm ³ /cm ³)	Total porosity, standard deviation (cm ³ /cm ³)	Range (mean ± one standard deviation)
MH	Loam	0.463	0.088	0.375–0.551
	Silty loam	0.501	0.081	0.420–0.582
	Silt	–	–	–
SM	Loamy sand	0.437	0.069	0.368–0.506
	Sandy loam	0.453	0.102	0.351–0.555
	Sandy clay loam	0.398	0.066	0.332–0.464

Quartz content

Low, medium, and high values of quartz content of the MH and SM soils are based on assumed soil compositions. Tarnawski et al. (1997) proposed the following equation for calculating the quartz content of a soil based on its mass fraction of clay, silt, sand, and gravel:

$$\text{Quartz content} = 0.05 \times M_{\text{Clay}} + 0.35 \times M_{\text{Silt}} + 0.80 \times M_{\text{Sand}} + 0.65 \times M_{\text{Gravel}}$$

where M_{xxx} is the mass fraction of each of the four soil components.

Tarnawski et al. also provided representative compositions of USDA soil textures; the ones for the soils of interest in this study are reproduced in Table 9. Substituting those soil mass fractions in the equation for quartz content produces the values of quartz content by soil type presented in the right hand column of Table 10. The range in quartz content is 0.36–0.51 for MH soil and 0.49–0.70 for SM soil. Applying the process described under “Experimental design” results in the low, medium, and high values of quartz content listed in Table 5.

Table 9. Proposed mass fractions of clay, silt, sand and gravel in USDA soil types. (From Tarnawski et al. 1997.)

Soil type (this study)	USDA soil texture	Clay	Silt	Sand	Gravel
MH	Loam	0.12	0.44	0.44	0.00
	Silty loam	0.12	0.70	0.18	0.00
	Silt	0.07	0.86	0.07	0.00
SM	Loamy sand	0.05	0.11	0.82	0.00
	Sandy loam	0.12	0.20	0.68	0.00
	Sandy clay loam	0.34	0.12	0.54	0.00

Table 10. Calculated quartz content (mass fraction) of USDA soil types based on soil components (Table 7). The quartz content of other soils is listed in Table B11 (Appendix B).

Soil type (this study)	USDA soil texture	Quartz content
MH	Loam	0.51
	Silty loam	0.40
	Silt	0.36
SM	Loamy sand	0.70
	Sandy loam	0.62
	Sandy clay loam	0.49

Specific heat

Low, medium, and high values of specific heat (J/kg-°C) of dry MH and SM soils are based on measurements reported by Steinmanis (1989) and reproduced in Table B18 (Appendix B). Steinmanis provided a range of values of specific heat of SM soil based on ten samples; it is 808.1–824.8 J/kg-°C. He did not provide data for MH soils, so, as with the thermal conductivity of dry soil (discussed above), his data for sixteen ML soil samples are substituted, which gives a range of 808.1–875.0 J/kg-°C. ML and MH are both fine-grained soils, including silts and fine sandy or silty soils; their different liquid limits and different plasticity, caused largely by the inclusion of soils with more clay content in the ML class, is the main distinction between them. Applying the process described under “Experimental design” results in the low, medium, and high values of specific heat of dry soil listed in Table 5.

Emissivity

Low, medium, and high values of emissivity of MH and SM soils are based on two sources (Appendix B): a summary of published values by Garratt (1992) and measurements by the Moderate Resolution Imaging Spectrometer (MODIS) Emissivity Library of the University of California, Santa Barbara (Appendix B). The MODIS measurements are made for wavelengths in the range of 3.335–15.152 microns; values in the range of 10–14 microns were selected for this study. Emissivities in Garratt’s summary range from 0.9 to 0.98; the spectral band is not reported other than as “longwave.” The emissivities used in this study are the same for both soils and are listed in Table 5.

4 Experiment notation

The notation used to identify each FASST simulation by soil factors and levels is given in Table 11. The entries in column 1 refer to joint-effect experiments, for which four soil factors were varied in combinations determined by the Greco-Latin square experiment design (Appendix A); these experiments were repeated for both soils (MH, SM) under sunny and cloudy weather scenarios. In Series 1 experiments, the four factors that are varied are thermal conductivity of the dry soil material (κ_{dry}), initial volumetric moisture content (ww), albedo (α), and bulk density (γ_d) of the dry soil. In Series 2 experiments, the four factors that are varied are porosity (n), quartz content (q), specific heat of dry soil material (C), and emissivity (ϵ). The level of each factor—low, medium, or high—is indicated by the subscript L, M, or H, respectively. The actual value of each soil factor at a given level is listed in Table 5. FASST runs on the standard soils are identified as MHS1, MHS2, SMS1, and SMS2, where S1 and S2 indicate Standard soil and series (1,2).

Table 11. Notation for identifying experiments in plots of predicted soil surface temperature.

Experiment	Factor 1	Factor 2	Factor 3	Factor 4
Series 1				
MH11, SM11	$K_{dry L}$	WW_L	α_L	$\gamma_d L$
MH12, SM12	$K_{dry L}$	WW_M	α_M	$\gamma_d M$
MH13, SM13	$K_{dry L}$	WW_H	α_H	$\gamma_d H$
MH14, SM14	$K_{dry M}$	WW_L	α_M	$\gamma_d M$
MH15, SM15	$K_{dry M}$	WW_M	α_H	$\gamma_d H$
MH16, SM16	$K_{dry M}$	WW_H	α_L	$\gamma_d L$
MH17, SM17	$K_{dry H}$	WW_L	α_H	$\gamma_d H$
MH18, SM18	$K_{dry H}$	WW_M	α_L	$\gamma_d L$
MH19, SM19	$K_{dry H}$	WW_H	α_M	$\gamma_d M$
Series 2				
MH21, SM21	n_L	q_L	C_L	ϵ_L
MH22, SM22	n_L	q_M	C_M	ϵ_M
MH23, SM23	n_L	q_H	C_H	ϵ_H
MH24, SM24	n_M	q_L	C_M	ϵ_M
MH25, SM25	n_M	q_M	C_H	ϵ_H
MH26, SM26	n_M	q_H	C_L	ϵ_L
MH27, SM27	n_H	q_L	C_H	ϵ_H
MH28, SM28	n_H	q_M	C_L	ϵ_L
MH29, SM29	n_H	q_H	C_M	ϵ_M

5 Experimental results

The results of FASST simulations are presented as time series plots (72 hours in length) of the difference in predicted soil surface temperature between a simulation conducted to investigate the effect of varying one or more soil parameters and an equivalent experiment with the associated standard soil. In all cases the soil, either MH or SM, is a single, 1-m-thick layer.

Single factor experiments

The variation in the predicted soil surface temperature caused by changes in the value (low, medium, or high) of a single soil factor is shown in Figures 5 through 11 and Figure 13. These experiments were done only for MH soil under the sunny weather scenario. (The results of varying soil moisture content of MH soil under sunny and cloudy weather conditions were presented in Figure 3.) For a given experiment, the values of the soil factors not being varied are those of the MH standard soil (MHS1 or MHS2). The quantity plotted is the surface temperature of the dry standard soil under sunny conditions minus the surface temperature of the experimental soil. On most of the plots, one curve shows a temperature difference of zero throughout the 72-hour period; this corresponds to the experimental soil that most closely (or exactly) matches the standard soil with which the experimental soils are compared. The other two curves typically show inverted trends, i.e., one curve having positive values while the other has negative values. When the experimental soil's predicted surface temperature is higher than that of the standard soil, the curve values are negative; when the experimental soil's predicted surface temperature is lower than that of the standard soil, the curve values are positive.

For several soil factors, the shape of the difference curve is determined by the 24-hour record of incident solar radiation (Fig. 1) that was used in creating the sunny weather scenario. The difference curves reflect 1) the proportion of a day (65%) that solar heating of the soil surface is occurring, and 2) the variation in incident solar radiation, including the secondary peak in the afternoon (approximately 1445 hours, or 0.7 fractional day).

The daily maximum effect of thermal conductivity on predicted soil surface temperature is approximately 0.12–0.15°C (Fig. 5). Peak daytime tem-

perature differences are approximately 50% larger (in absolute value) than peak nighttime differences. Of the three soil conditions, the surface of the low-thermal-conductivity soil is the hottest soil during daylight hours, when solar heating of the soil surface is occurring, because heat is less readily conducted from the surface into the soil layer. At night, when radiational cooling of the soil is occurring, the low-thermal-conductivity soil is coldest because heat is less readily conducted from the relatively warm interior of the soil layer to the colder surface. For the high-thermal-conductivity soil, the situation is reversed: the coolest surface is in the daytime, and the warmest surface is at night.

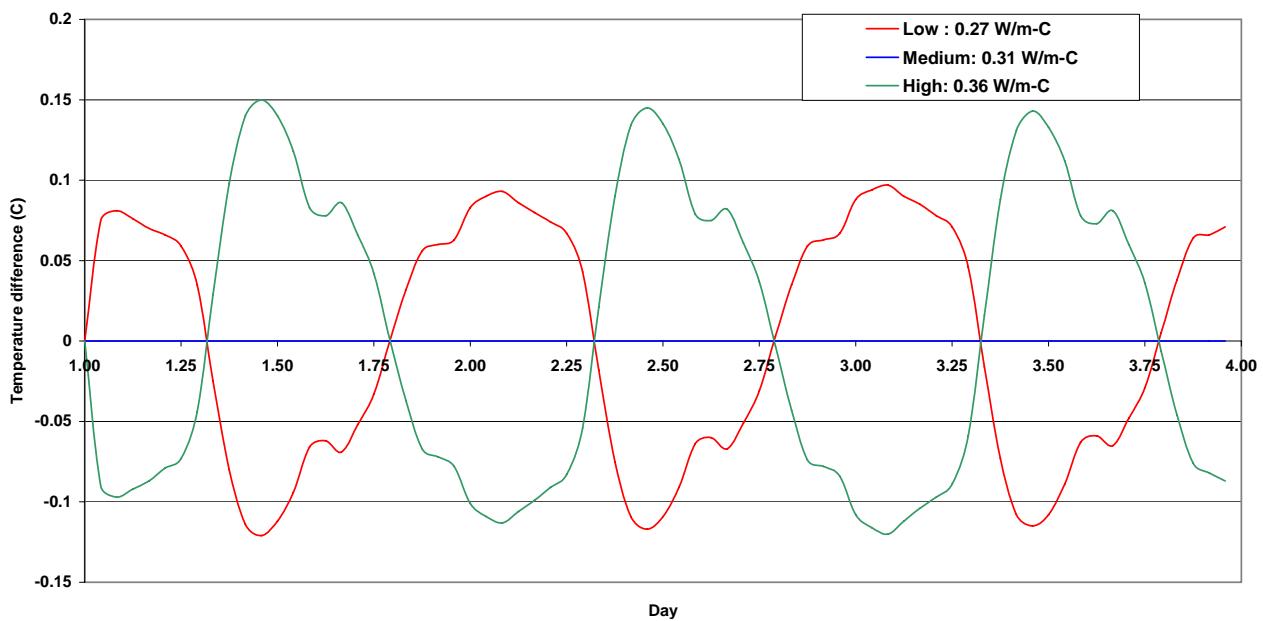
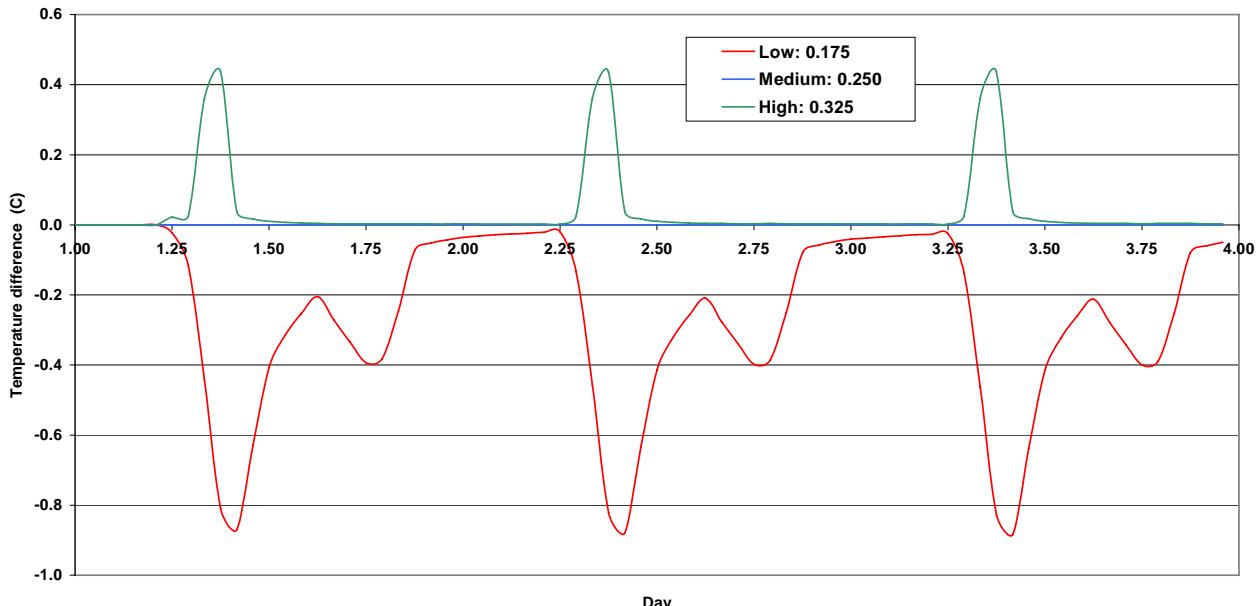
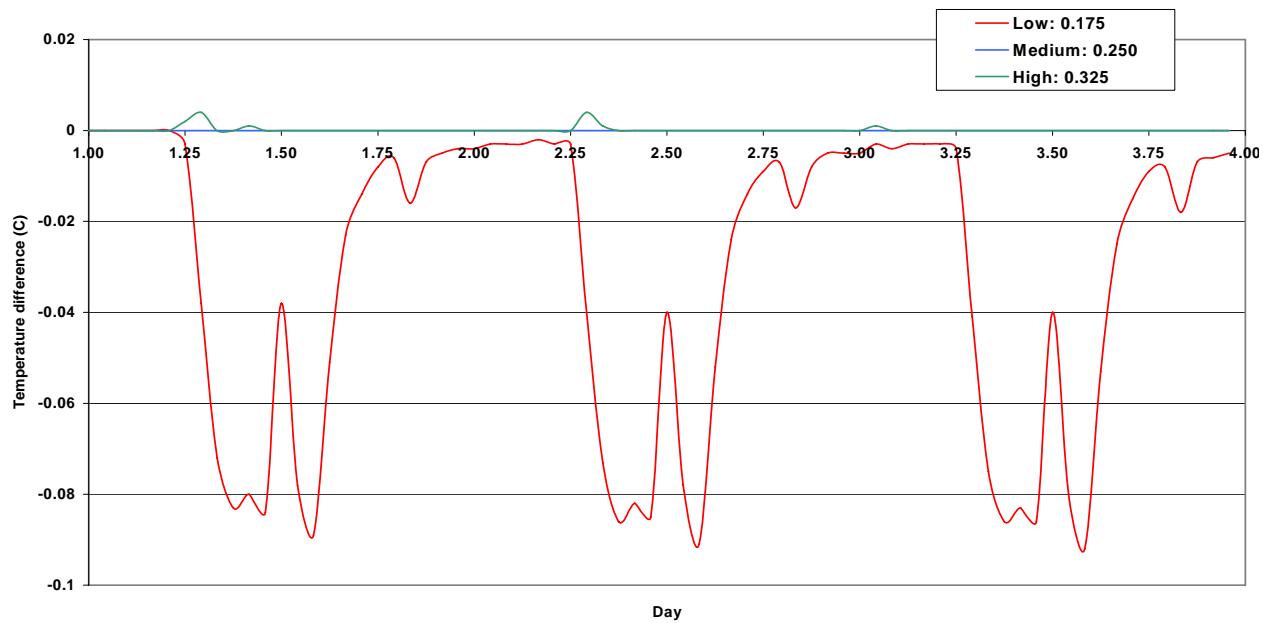


Figure 5. Difference in soil surface temperature (MHS1 minus experimental soil) for low, medium, and high values of thermal conductivity of the dry soil material. The temperature difference is zero with the medium-thermal-conductivity soil because its soil parameter values identically match those of the standard soil to which it is compared.

The magnitude of the albedo effect on predicted soil surface temperature is weather dependent, being a maximum of approximately 0.9°C under sunny conditions when solar loading is strong (Fig. 6a) but only approximately 0.1°C under cloudy conditions (Fig. 6b). Regardless of the relative solar loading (sunny vs. cloudy conditions), the low-albedo soil has the hottest soil surface and shows more variation in temperature with perturbations in incident solar radiation. That the low-albedo soil would have the hottest surface is consistent with greater absorption (less reflection) of solar radiation. The albedo effect is not linear. The change in surface temperature caused by decreasing the albedo from 0.25 to 0.175 is two (sunny conditions) to ten (cloudy conditions) times larger than the



a. Sunny weather conditions.



b. Cloudy weather conditions.

Figure 6. Difference in soil surface temperature (MHS1 minus experimental soil) for low, medium, and high values of albedo under sunny and cloudy weather conditions. The temperature difference is zero with the medium-albedo soil because its soil parameter values identically match those of the standard soil to which it is compared.

change that results from increasing the albedo from 0.25 to 0.325. Under sunny conditions the albedo effect is strongest in the morning: the temperature difference is zero before the onset of solar heating (Fig. 1), then increases rapidly as the amount of incident solar radiation increases steadily. As the rate of increase in received solar radiation lessens in mid-

morning, the temperature difference due to the albedo effect reaches a maximum. Had the day been overcast in the morning and sunny in the afternoon, then the timing of the pronounced temperature difference would have been shifted to the afternoon to coincide with solar heating of the soil. On days with intermittent cloud cover, such that there are repeated episodes of solar heating of the soil, there could be significant surface temperature differentials reoccurring throughout the day. Similarly, on a cloudy day (Fig. 6b) the temperature differences will be small, but they may fluctuate throughout the daylight hours.

The daily maximum effect of bulk density on the predicted soil surface temperature is approximately 0.8–1.0°C (Fig. 7). The peak daytime temperature differences are approximately 50% larger (in absolute value) than the peak nighttime differences. The dry bulk density affects the calculated thermal conductivity of the soil, which depends on the thermal conductivity of the dry soil material, the amount of pore space (derived from bulk density and intrinsic density), and the volumetric soil moisture content (how much pore space is filled with water vs. air). For a given moisture content and thermal conductivity of the dry soil material, the soil's calculated thermal conductivity is lower the lower its bulk density. That is why the curves of Figure 7, the bulk density effect, mimic the curves of Figure

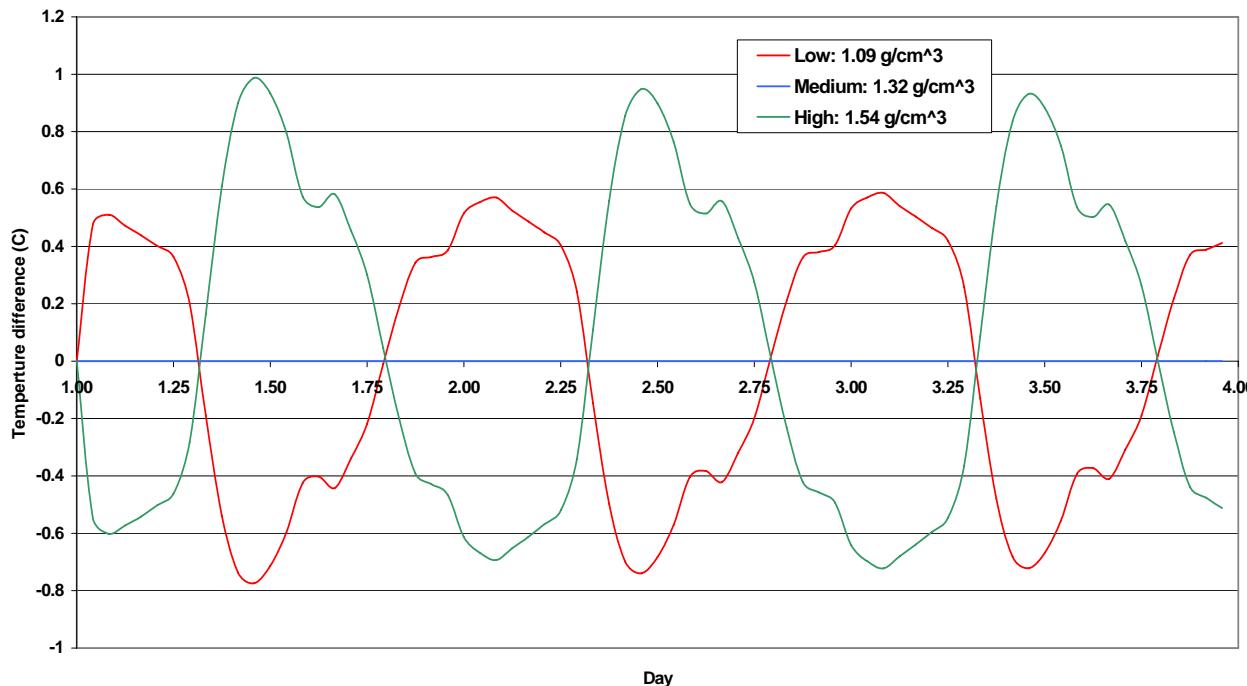


Figure 7. Difference in soil surface temperature (MHS1 minus experimental soil) for low, medium, and high values of dry soil bulk density. The temperature difference is zero with the medium-bulk-density soil because its soil parameter values identically match those of the standard soil to which it is compared.

5, the thermal conductivity effect. The magnitude of the bulk density effect, however, is about six times that of the dry thermal conductivity effect. This indicates that accurate representation of the amounts of soil constituents (dry soil material, air, and water) that jointly determine the soil's thermal conductivity is more crucial than accurately specifying the dry soil thermal conductivity by itself.

The effect of porosity on the predicted soil surface temperature (Fig. 8) is the inverse of the bulk density effect. The thermal conductivity of the dry soil material for these experiments is $0.31 \text{ W/m} \cdot \text{^{\circ}C}$, ten times that of air (approximately $0.025 \text{ W/m} \cdot \text{^{\circ}C}$), so low porosity corresponds to relatively high soil thermal conductivity, because more of a given volume of soil is filled with soil particles rather than air. High thermal conductivity results in relatively low daytime surface temperatures, because heat is readily transferred into the soil from the surface, and relatively high nighttime surface temperatures, because heat flows readily from the interior to the soil surface. The daily maximum porosity effect on soil surface temperature is approximately $0.5\text{--}0.7^{\circ}\text{C}$. For these experiments, thermal conductivity of the dry soil and porosity were specified, but bulk density was flagged as unknown. Comparison of Figures 7 and 8 shows that, although both parameters influence soil surface temperature through the dependence of soil thermal conductivity on the amount of air-filled void space, variation in bulk density produces a change in surface soil temperature that is approximately 50% larger.

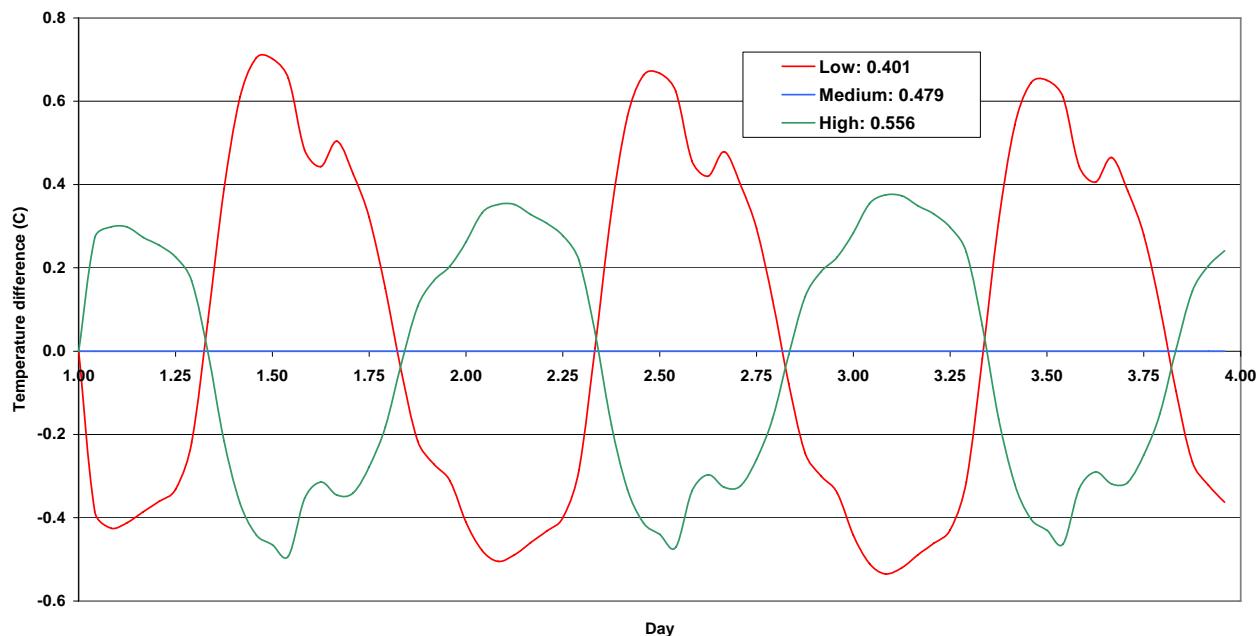


Figure 8. Difference in soil surface temperature (MHS2 minus experimental soil) for low, medium, and high values of soil porosity. The temperature difference is zero with the medium-porosity soil because its soil parameter values identically match those of the standard soil to which it is compared.

Three soil factors—quartz content (Fig. 9), specific heat (Fig. 10), and emissivity (Fig. 11)—have negligible effects on the predicted soil surface temperature. The effect of quartz content produces minor daily peak differences in surface temperature through its influence on the calculated soil thermal conductivity. The specific heat “effect” may actually be model noise, but it is consistent with the common understanding that specific heat is not a primary factor in predicting soil temperature. The emissivity effect is intuitively correct: for a given heat exchange, a low (high) emissivity correlates with a higher (lower) soil surface temperature, so the temperature difference with the standard soil is negative (positive). To further investigate the emissivity effect, FASST simulations were run for emissivity values of 0.1–1.0, with the results shown in Figure 12; this range includes values of emissivity that are not physically relevant for soil. Figure 12 reinforces that material emissivity is a minor factor in predicting surface temperature with FASST, i.e., the value of emissivity assigned to a soil must be greatly in error before the predicted soil surface temperature is off by more than a few tenths of a degree.

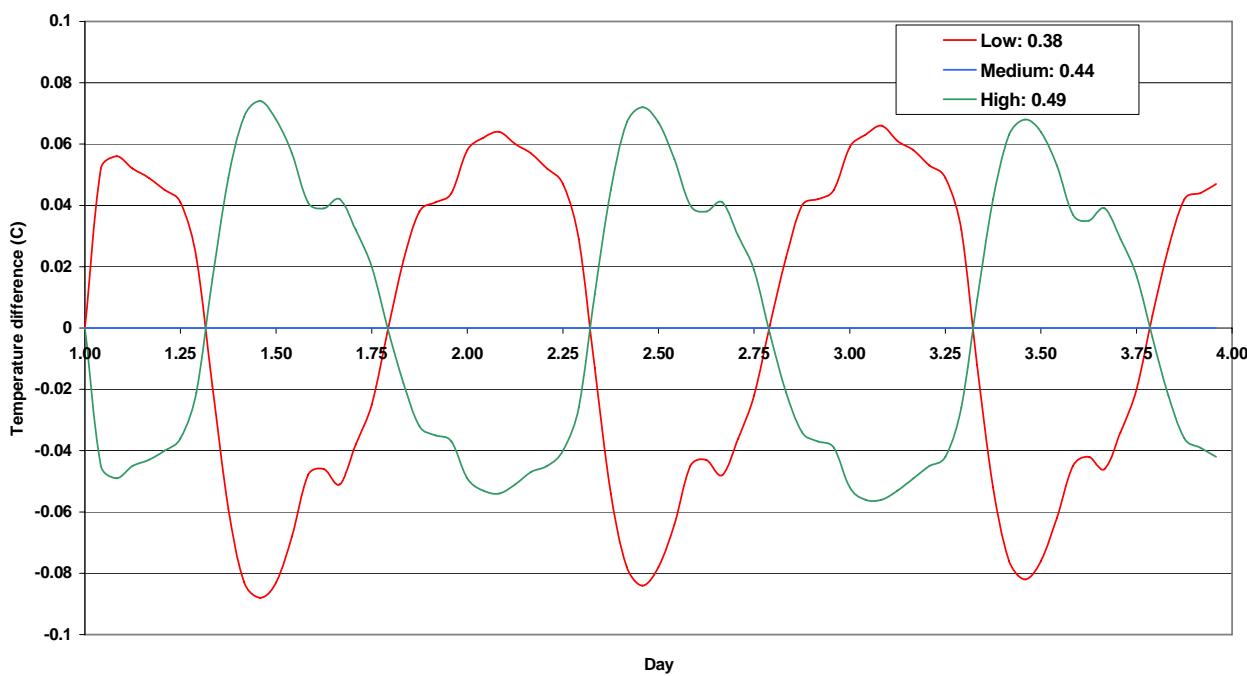


Figure 9. Difference in soil surface temperature (MHS2 minus experimental soil) for low, medium, and high values of quartz content. The temperature difference is zero with the medium-quartz-content soil because its soil parameter values identically match those of the standard soil to which it is compared.

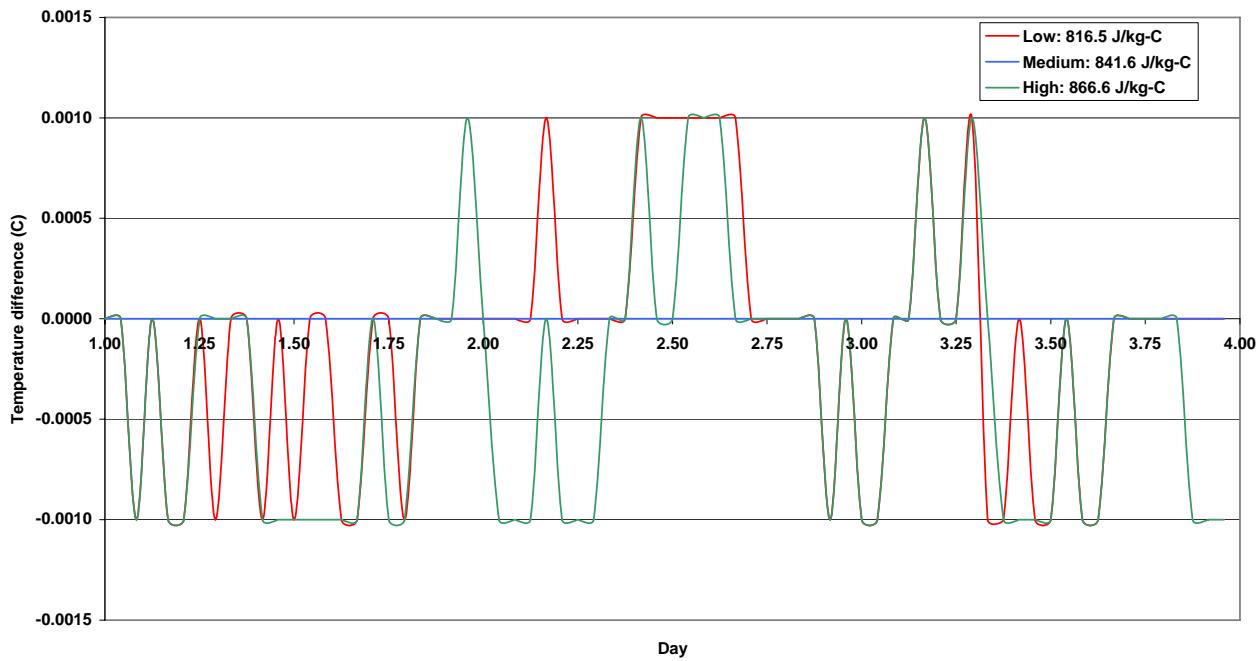


Figure 10. Difference in soil surface temperature (MHS2 minus experimental soil) for low, medium, and high values of specific heat of dry soil material. The temperature difference is zero with the medium-specific-heat soil because its soil parameter values identically match those of the standard soil to which it is compared.

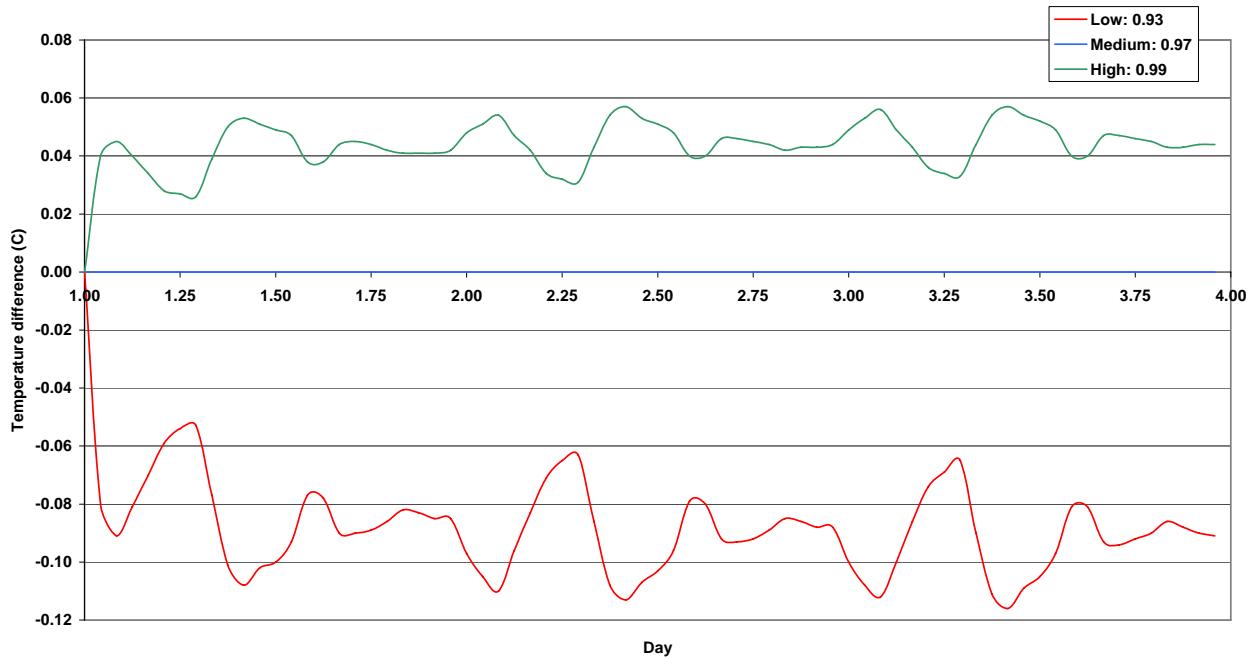


Figure 11. Difference in soil surface temperature (MHS2 minus experimental soil) for low, medium, and high values of emissivity. The temperature difference is zero with the medium-emissivity soil because its soil parameter values identically match those of the standard soil to which it is compared.

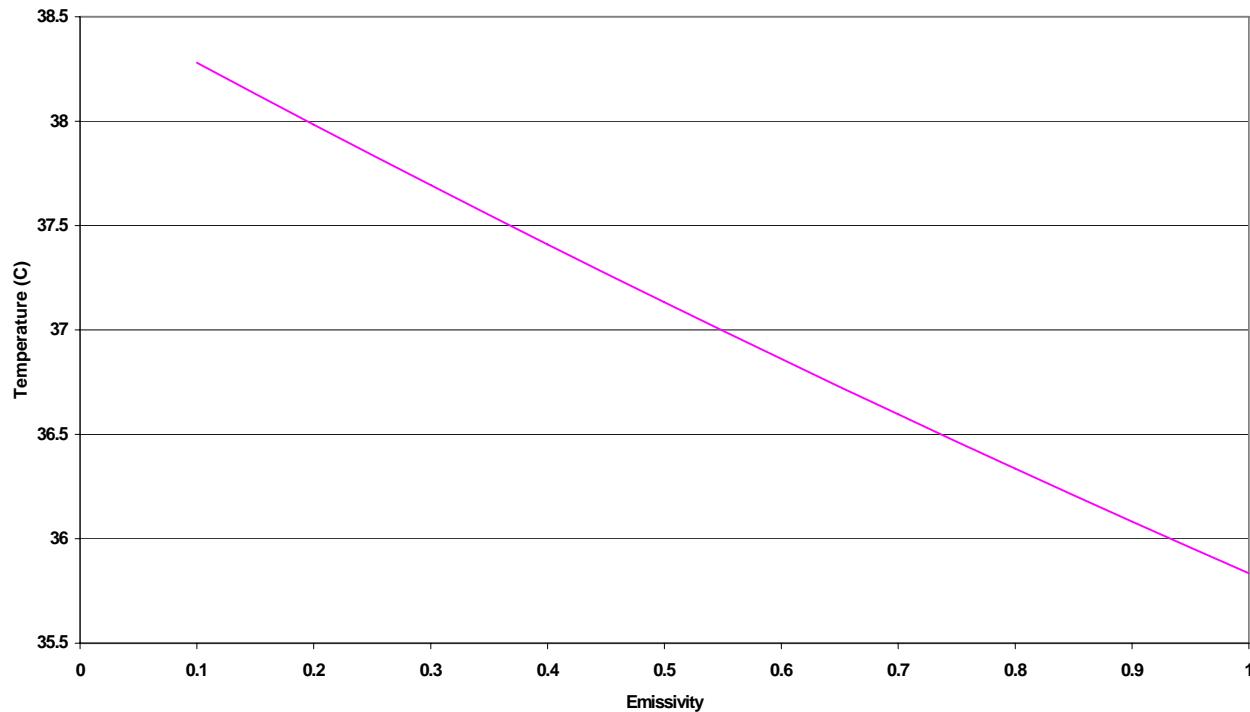


Figure 12. Change in predicted surface temperature with variation in a material's emissivity. Other material parameters used in the FASST simulations that produced this curve are those of MHS1 soil.

The effect of initial moisture content on the predicted soil surface temperature is shown in Figure 13. With this soil parameter it is the low-value soil (with a volumetric moisture content of 11%) that matches the standard soil (MHS1) and so shows zero temperature difference, while the wetter soils have daily peak temperature differences of approximately 1.2–1.6°C. The moisture effect curves have the same diurnal variation trends as the other soil properties that affect the thermal conductivity of the soil: thermal conductivity of the dry soil material, bulk density, and porosity. With increasing moisture content, more of the void space in the soil is filled with water, which has a thermal conductivity on the order of 0.57 W/m·°C, than with air, which has a thermal conductivity on the order of 0.025 W/m·°C, so the effective thermal conductivity of the soil increases. During daytime solar heating, heat more readily conducts into soil with a higher thermal conductivity, so the soil's surface temperature is lower. At night, during radiational cooling of the soil, heat more readily conducts to the surface of high-thermal-conductivity soil, so that soil has a higher surface temperature. The result is a trend of increasing temperature differences (in absolute value) with increasing moisture content.

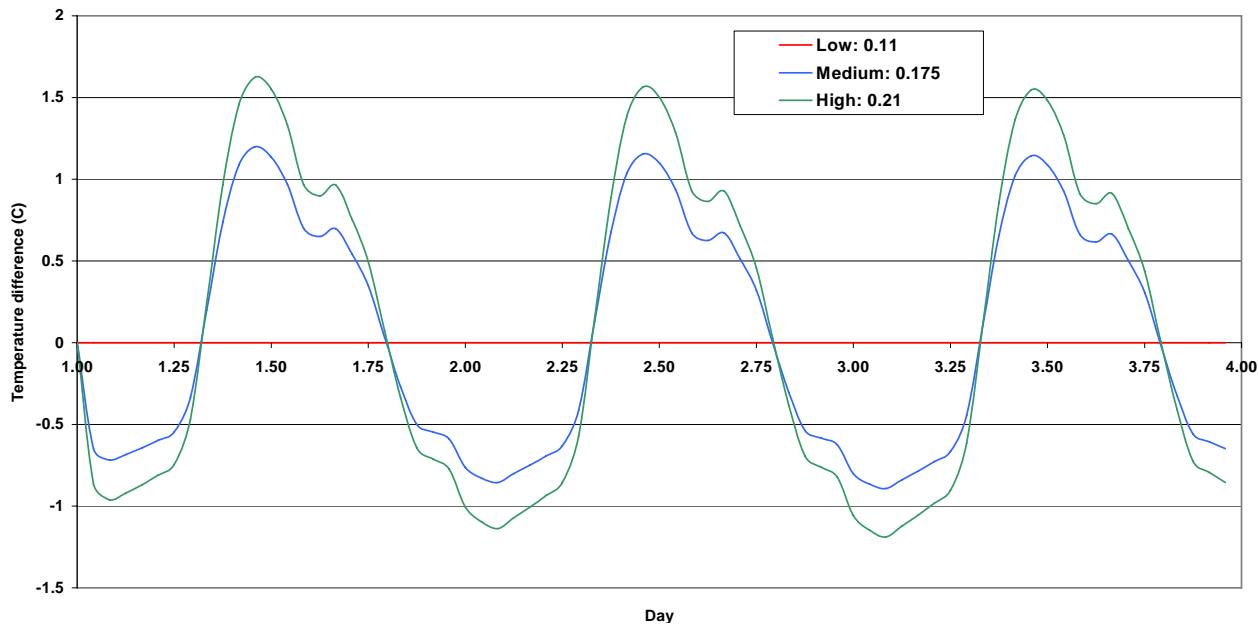


Figure 13. Difference in soil surface temperature (MHS1 minus experimental soil) for low, medium, and high values of initial volumetric moisture content. The temperature difference is zero with the low-moisture-content soil because its soil parameter values identically match those of the standard soil to which it is compared.

Summary of results with single factor experiments

Relative to the reference MH soil (fine-grained, non-clay), a change in the value of a soil parameter causes a change in the predicted soil surface temperature that ranges from negligible (quartz content, specific heat of the dry soil material, emissivity, and, on cloudy days, albedo) to as much as 1.6°C (volumetric moisture content). Rated according to the magnitude of the change in soil surface temperature they cause, the significance of the soil factors in descending order is: volumetric soil moisture content, bulk density of the dry soil material, albedo (sunny days), porosity, thermal conductivity, and others (quartz content, specific heat, emissivity).

Multiple factor experiments

A. Series 1 experiments

The results of Series 1 sunny weather experiments with MH and SM soils are presented in Figures 14 and 15, respectively. These experiments varied the values of three of the following four soil parameters with each experiment: thermal conductivity of dry soil material, initial moisture content, albedo, and bulk density. Table 11 relates the values of the soil parameters to a given experiment, as indicated by the curve label. Maximum differences in predicted soil surface temperatures (relative to standard soil) are approximately 2°C or less. The results from the corresponding experi-

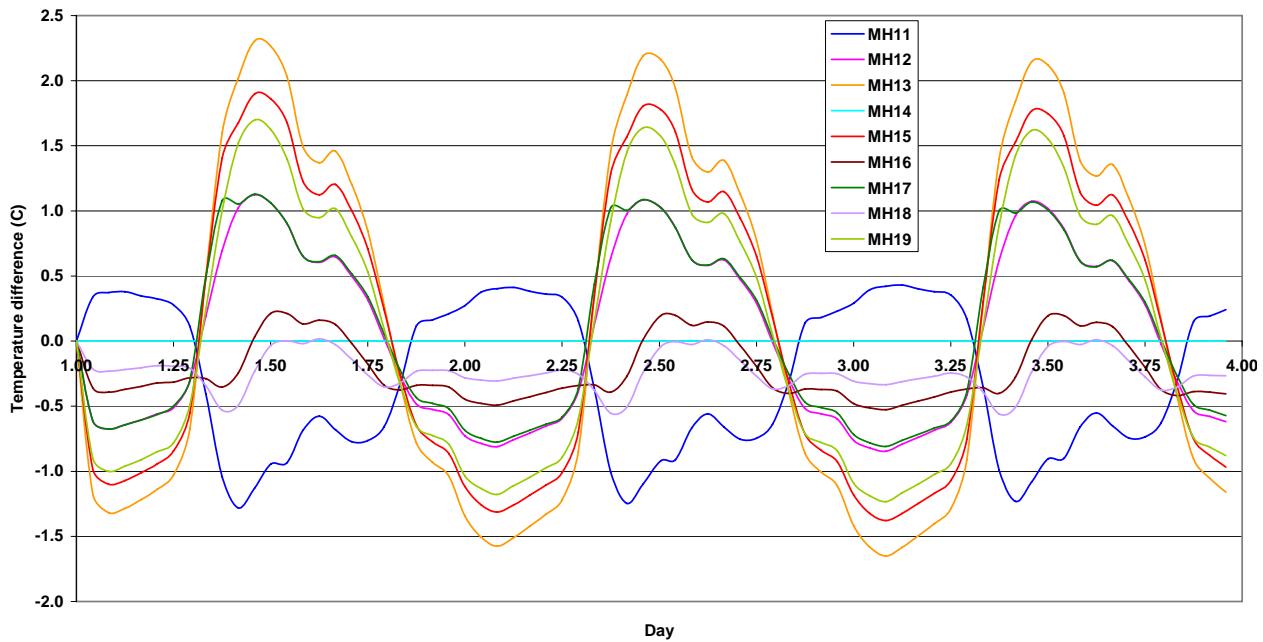


Figure 14. Differences (relative to MH standard soil) in predicted surface temperature during the 72-hour sunny weather simulations for MH soil with Series 1 soil parameters. The gross features of the curves are similar. Curve MH11 is notably out of phase because, relative to the standard soil's surface temperature, its associated predicted surface temperature is higher (lower) when the other soil cases result in surface temperatures that mostly are lower (higher), causing temperature differences that are opposite in sign.

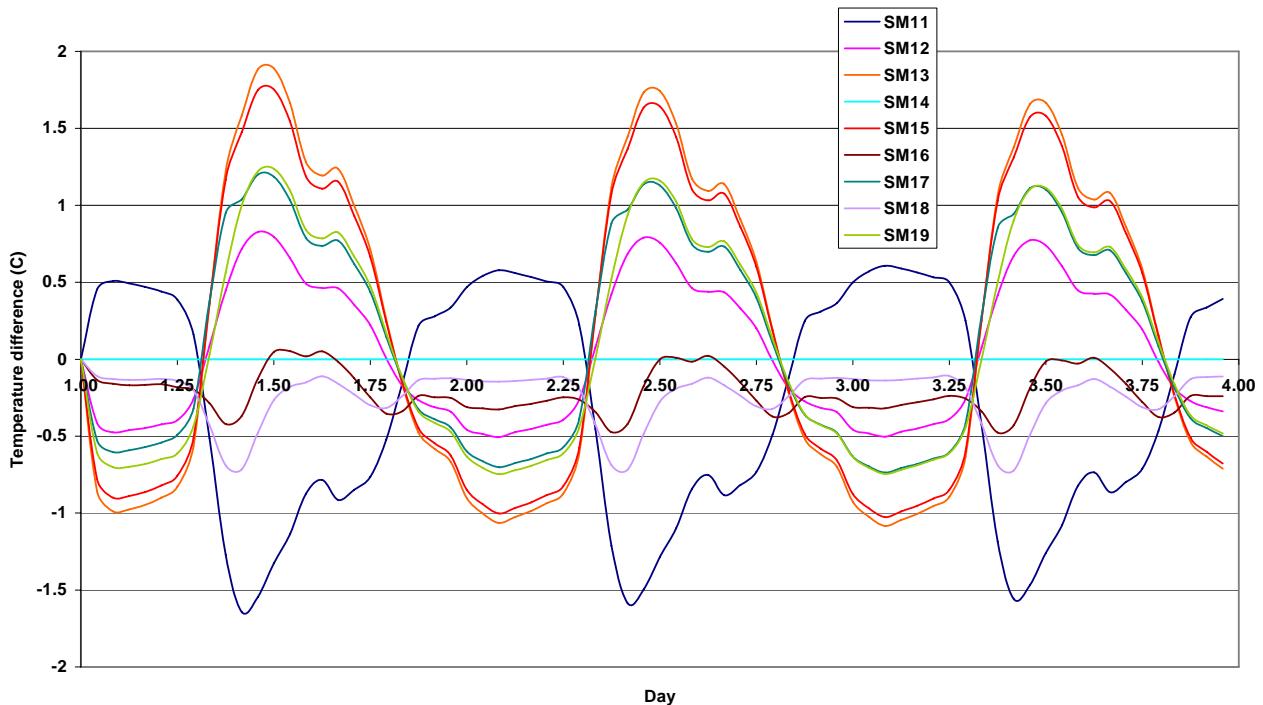


Figure 15. Differences (relative to SM standard soil) in predicted surface temperature during the 72-hour sunny weather simulations for SM soil with Series 1 soil parameters. The gross features of the curves are similar. Curve SM11 is notably out of phase because, relative to the standard soil's surface temperature, its associated predicted surface temperature is higher (lower) when the other soil cases result in surface temperatures that mostly are lower (higher), causing temperature differences that are opposite in sign. The temperature scale is changed from Figure 14 to make small temperature differences easier to distinguish.

ments under cloudy weather conditions are summarized in Figures 16 and 17 for MH and SM soils, respectively; temperature differences relative to standard soils are significantly smaller under cloudy conditions. Soil type (MH vs. SM) affects the magnitude of daytime or nighttime temperature differences by less than 0.5°C (sunny conditions) or 0.2°C (cloudy conditions).

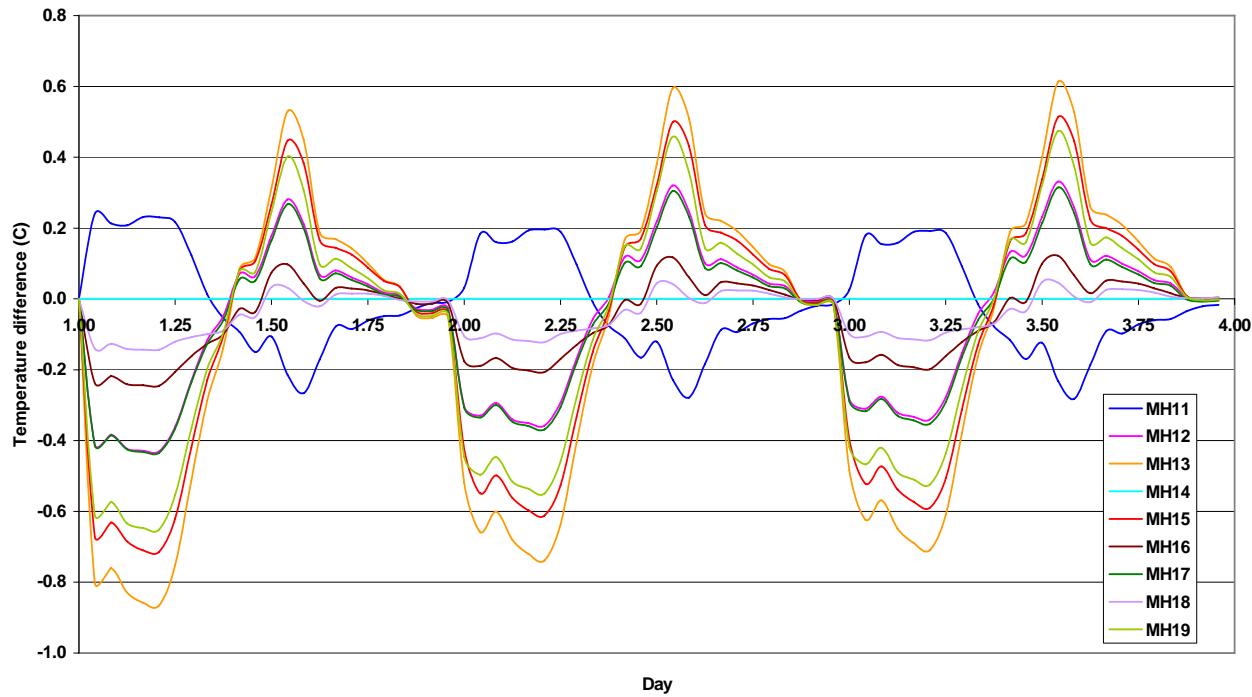


Figure 16. Differences (relative to MH standard soil) in predicted surface temperature during the 72-hour cloudy weather simulations for MH soil with Series 1 soil parameters. The gross features of the curves are similar. Curve MH11 is notably out of phase because, relative to the standard soil's surface temperature, its associated predicted surface temperature is higher (lower) when the other soil cases result in surface temperatures that mostly are lower (higher), causing temperature differences that are opposite in sign.

The MH14 and SM14 experiments duplicate the standard soil experiments for this series, which is why the temperature difference associated with them is 0°C under sunny and cloudy conditions.

The Series 1 experiments include as variables some of the most significant soil parameters, as determined with the single factor experiments that were done with MH soil: moisture content, albedo, and bulk density. The largest change in soil surface temperature (relative to the standard MH soil) that variation in a single soil factor caused was 1.6°C, but several of the Series 1 experiments under sunny weather conditions produce larger changes, with a maximum change of approximately 2.4°C. With other combinations of values of soil parameters, the temperature difference relative to the standard soil is negligible. This points out that, when the values

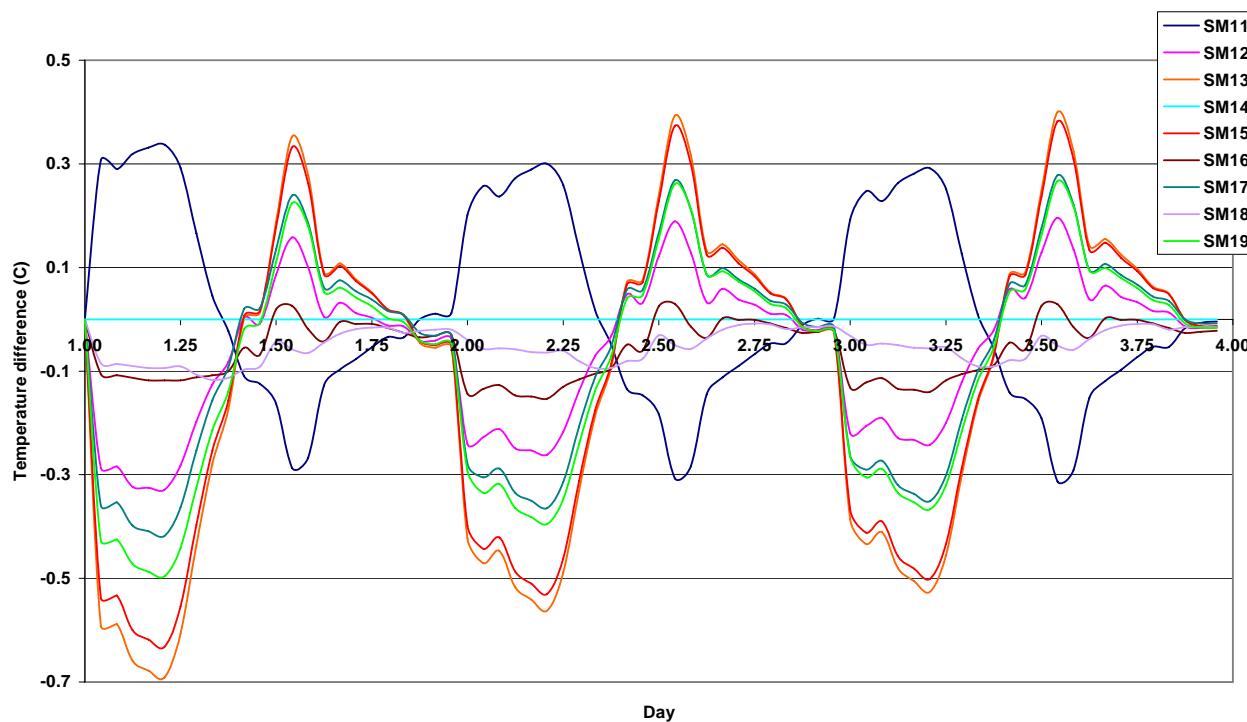


Figure 17. Differences (relative to SM standard soil) in predicted surface temperature during the 72-hour cloudy weather simulations for SM soil with Series 1 soil parameters. The gross features of the curves are similar. Curve SM11 is notably out of phase because, relative to the standard soil's surface temperature, its associated predicted surface temperature is higher (lower) when the other soil cases result in surface temperatures that mostly are lower (higher), causing temperature differences that are opposite in sign. The temperature scale is changed from Figure 16 to make small temperature differences easier to distinguish.

of soil parameters for use with FASST are estimated from a soil properties database rather than known from measurements of the physical soil's properties, it is difficult to predict the size of the surface temperature differential between the simulated soil and the physical soil. The Series 1 results do indicate, however, that the temperature differential is likely to be a few degrees at most under sunny conditions, and significantly less under cloudy conditions. [Note that the temperature differential discussed here is due only to the correctness of the selected soil parameter values (how well they characterize the actual soil) and does not reflect the margin of error inherent with FASST predictions.]

Of all the combinations of soil type, weather condition, and soil parameters, the temperature difference associated with experiment 18 (MH18, SM18) is consistently less than 0.5°C. Yet, the Series 1 soil parameters for this experiment have no values in common with the standard soils (MHS1, SMS1) with which they are compared. This highlights that, when simulating a physical soil, the net effect of selected values of FASST soil parameters can be close agreement between predicted and actual soil temperatures even if each individual parameter value is not optimized for the physical soil.

B. Series 2 experiments

The results of Series 2 experiments with MH and SM soils under sunny and cloudy conditions are presented in Figures 18 through 21. These experiments varied the values of three of the following four soil parameters with each experiment: porosity, quartz content, specific heat of dry soil material, and emissivity. Table 11 relates the values of the soil parameters to a given experiment, as indicated by the curve label. The obvious feature of these plots is that the curves of temperature difference are grouped by porosity. This is consistent with the single factor experiments, which had shown that varying the value of porosity caused a larger change in predicted surface temperature than did variations in quartz content, specific heat, or emissivity.

Unlike the Series 1 experiments, where changing the values of several soil parameters for a single simulation could result in a temperature difference, relative to the standard soil, that was much larger than any one soil parameter could account for, the temperature differences associated with Series 2 experiments are not more than 0.3°C larger than those caused by varying porosity by itself. This again is consistent with porosity being the only Series 2 soil parameter that significantly affects the predicted soil surface temperature.

Accurate characterization of a soil in terms of its quartz content, dry specific heat, and emissivity is secondary in importance to assigning an appropriate porosity to the soil. The porosity of a given soil can be provided to FASST as direct input, as was done with these Series 2 experiments, or it can be calculated by FASST (or the user) if the bulk density and intrinsic density of the soil when dry are known.

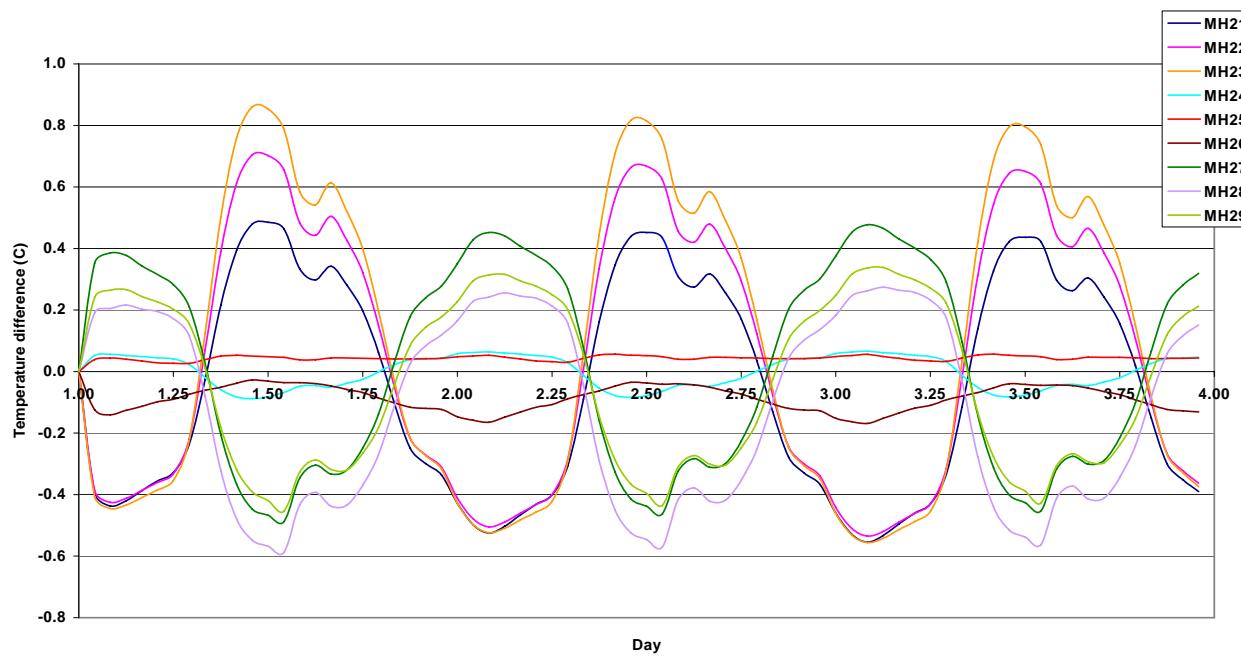


Figure 18. Differences (relative to MH standard soil) in the predicted surface temperature during the 72-hour sunny weather simulations for MH soil with Series 2 soil parameters. The curves of temperature difference group by porosity: low porosity relative to the standard soil results in daytime surface temperatures that are lower (positive temperature difference) and nighttime surface temperatures that are higher (negative temperature difference) through its effect on the soil's thermal conductivity. The thermal conductivity of the dry soil material for these experiments is $0.31 \text{ W/m} \cdot \text{°C}$, ten times that of air (approximately $0.025 \text{ W/m} \cdot \text{°C}$), so low porosity corresponds to relatively high soil thermal conductivity, because more of a given volume of soil is filled with soil particles rather than air.

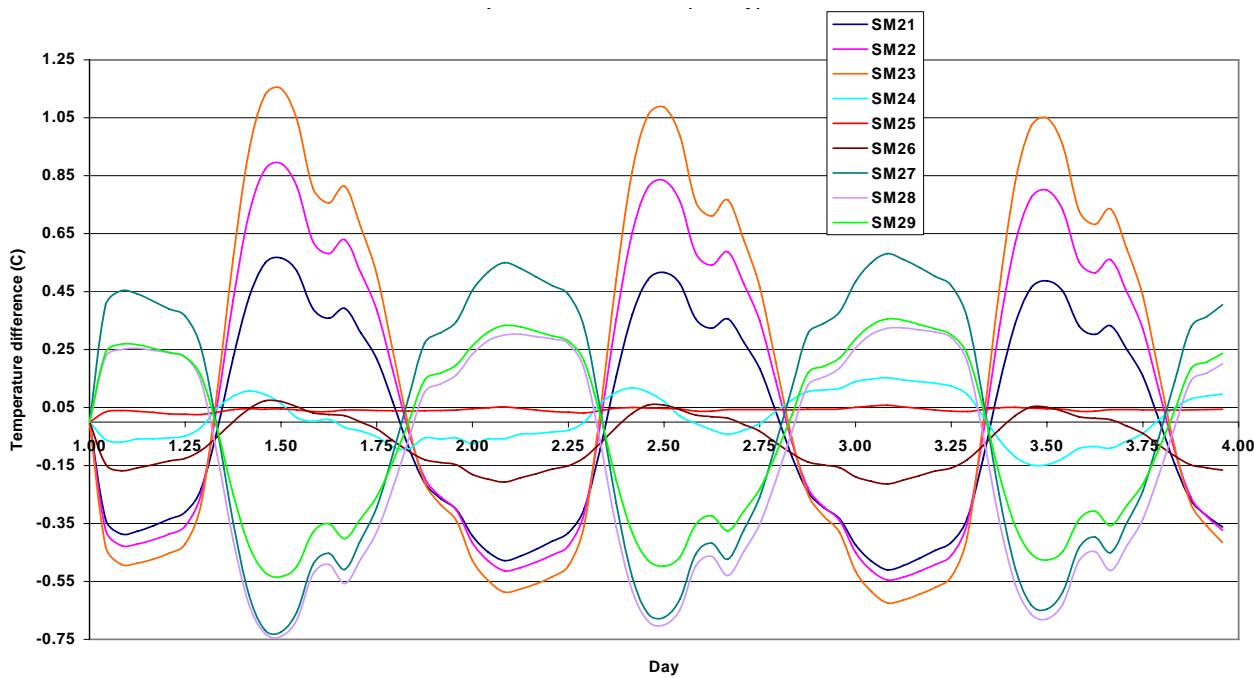


Figure 19. Differences (relative to SM standard soil) in the predicted surface temperature during the 72-hour sunny weather simulations for SM soil with Series 2 soil parameters. The curves of temperature difference group by porosity: low porosity relative to the standard soil results in daytime surface temperatures that are lower (positive temperature difference) and nighttime surface temperatures that are higher (negative temperature difference) through its effect on the soil's thermal conductivity. The thermal conductivity of the dry soil material for these experiments is $0.56 \text{ W/m} \cdot \text{°C}$, twenty times that of air (approximately $0.025 \text{ W/m} \cdot \text{°C}$), so low porosity corresponds to relatively high soil thermal conductivity, because more of a given volume of soil is filled with soil particles rather than air. The temperature scale is changed from Figure 18 to make small temperature differences easier to distinguish.

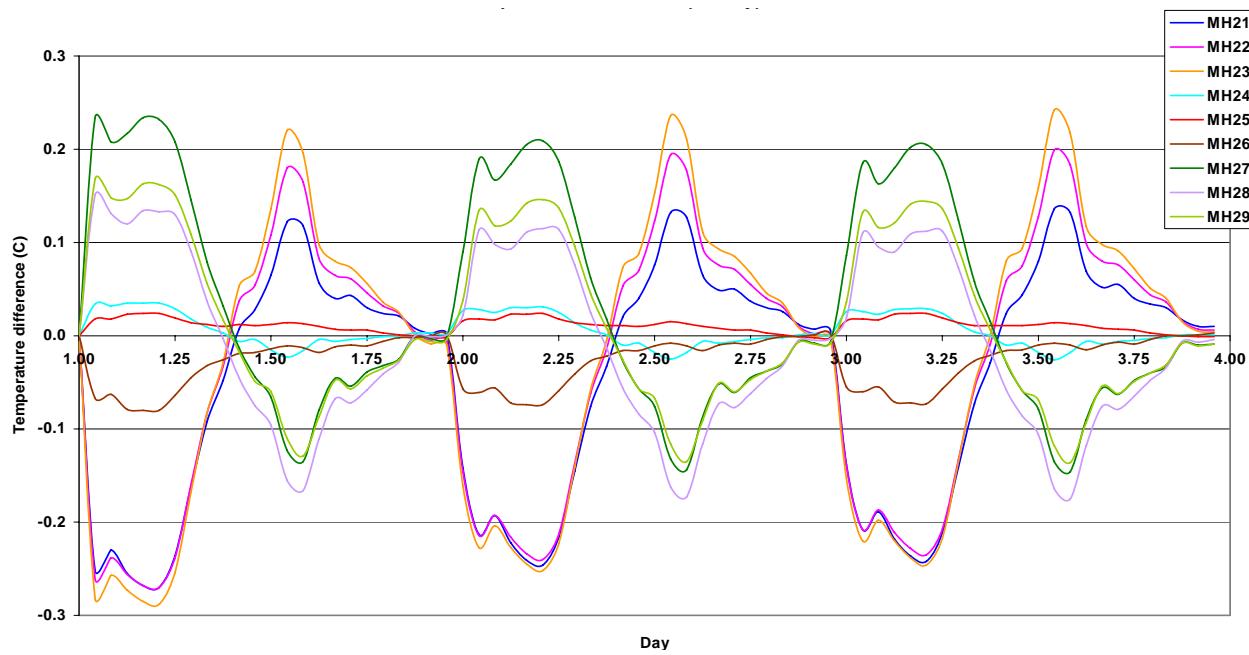


Figure 20. Differences (relative to MH standard soil) in the predicted surface temperature during the 72-hour cloudy weather simulations for MH soil with Series 2 soil parameters. The curves of temperature difference group by porosity: low porosity relative to the standard soil results in daytime surface temperatures that are lower (positive temperature difference) and nighttime surface temperatures that are higher (negative temperature difference) through its effect on the soil's thermal conductivity. The thermal conductivity of the dry soil material for these experiments is $0.31 \text{ W/m} \cdot \text{°C}$, ten times that of air (approximately $0.025 \text{ W/m} \cdot \text{°C}$), so low porosity corresponds to relatively high soil thermal conductivity, because more of a given volume of soil is filled with soil particles rather than air.

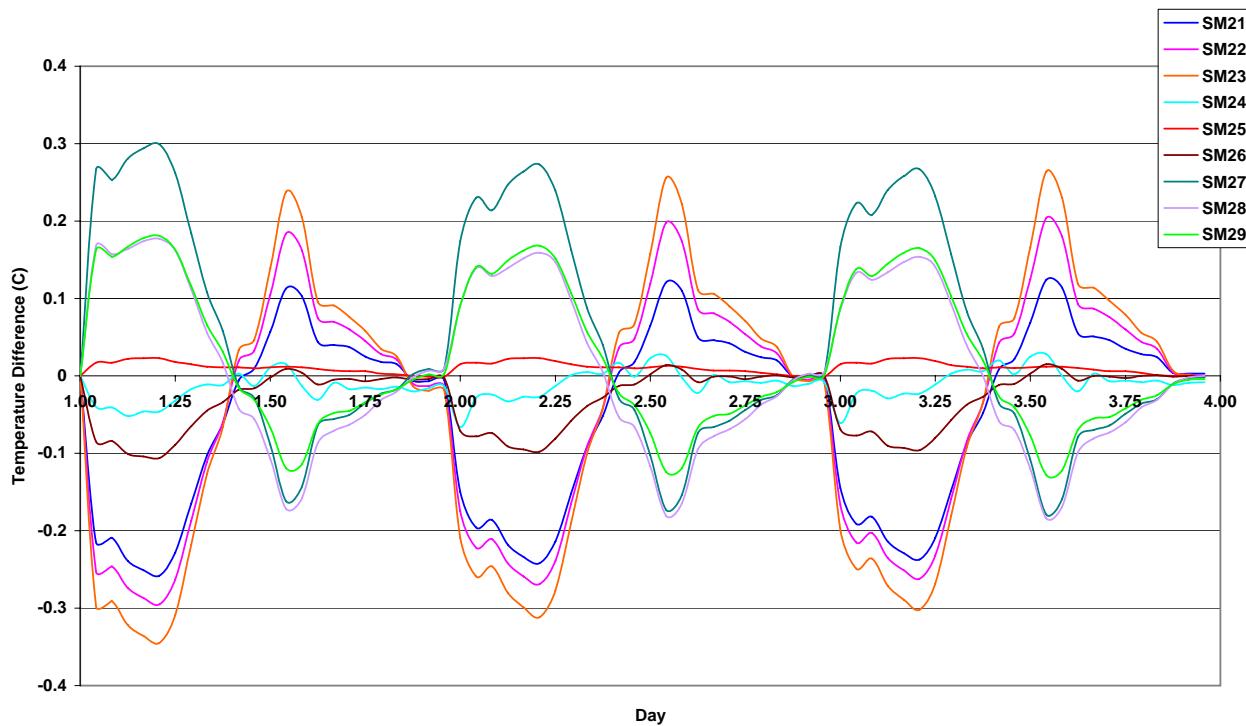


Figure 21. Differences (relative to SM standard soil) in the predicted surface temperature during the 72-hour cloudy weather simulations for SM soil with Series 2 soil parameters. The curves of temperature difference group by porosity: low porosity relative to the standard soil results in daytime surface temperatures that are lower (positive temperature difference) and nighttime surface temperatures that are higher (negative temperature difference) through its effect on the soil's thermal conductivity. The thermal conductivity of the dry soil material for these experiments is $0.56 \text{ W/m} \cdot \text{C}$, twenty times that of air (approximately $0.025 \text{ W/m} \cdot \text{C}$), so low porosity corresponds to relatively high soil thermal conductivity, because more of a given volume of soil is filled with soil particles rather than air. The temperature scale is changed from Figure 20 to make small temperature differences easier to distinguish.

6 Conclusions

Single factor experiments have shown that the major soil parameters for FASST predictions of soil surface temperature are, in descending order, initial volumetric soil moisture content, bulk density of the dry soil material, albedo (sunny days), and porosity. The thermal conductivity of the dry soil material has a minor effect on predicted soil temperature. Quartz content, specific heat of the dry soil material, and emissivity each has a negligible effect on predicted soil temperature.

Series 1 and Series 2 experiments investigated the effect on predicted soil surface temperature of varying three factors for any one simulation. Temperature differences (relative to a standard soil) for some combinations of factors were larger than were obtained by varying a single major soil factor. This highlights the difficulty of associating a measure of confidence with a given FASST simulation, i.e., how closely predicted temperatures will match actual soil temperatures for a given soil type and weather scenario, given that the predicted temperature depends on the cumulative effect of the accuracy of the value assigned to each of the significant soil parameters.

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Appendix A. Greco-Latin square experimental design for variability of predicted soil surface temperatures

The factors influencing predicted surface temperatures obtained with FASST are separated into two categories in terms of expected magnitude of influence. Prior to this study, the major factors were thought to be the thermal conductivity of the dry soil material, the soil's water content, its albedo, and the bulk density of the dry soil material. Minor factors were thought to be the soil's porosity, quartz content, emissivity, and the specific heat of the dry soil material. Having two categories allows the relative significance of factors with similar order-of-magnitude influence to be determined.

Three levels of effect are investigated for each factor. They represent high, medium, and low values of the factor. The procedure for determining the values for each level is presented here, using thermal conductivity as an example.

1. The range in thermal conductivity of a given soil type is $R = K_2 - K_1$ (W/m-°C), where $K_1 < K_2$ and K_1 (K_2) is the lowest (highest) reported thermal conductivity for a soil sample (taken from a compilation of soil properties provided by Peck).
2. $R/8$ establishes the size of this soil's thermal conductivity "bin."
3. Nine discrete thermal conductivity values are determined as shown in Table A1, with three each in the low, medium, and high categories.
4. The middle value is selected from each of the three categories and is referred to as that soil type's representative low, medium, or high thermal conductivity level.

The experimental design used is the Greco-Latin square. The Latin square design is appropriate when there are more than two levels (three are used in the FASST study) and when it is already known that there are no or only negligible interactions between factors. The Latin square design allows estimation of the main effects of all factors in the design in an unbiased manner. For example, three factors (albedo, thermal conductivity, and water content) with three levels (low, medium, and high) could be assessed with nine experiments (Table A2).

Table A1. Relationship between three levels of a given factor (e.g., thermal conductivity) and the range of values of that factor for a given soil type.

Thermal conductivity value	Thermal conductivity category	Thermal conductivity level
K_1	Low	
$K_1 + (R/8)$	Low	Low
$K_1 + [2 \times (R/8)]$	Low	
$K_1 + [3 \times (R/8)]$	Medium	
$K_1 + [4 \times (R/8)]$	Medium	Medium
$K_1 + [5 \times (R/8)]$	Medium	
$K_1 + [6 \times (R/8)]$	High	
$K_1 + [7 \times (R/8)]$	High	High
$K_1 + [8 \times (R/8)]$, or K_2	High	

Table A2. Example of a Latin square design for three factors and three levels. The entries in italics are those of Factor 3 (e.g., water content).

	Factor 2 (e.g., thermal conductivity of dry material)		
Factor 1 (e.g., albedo)	Low	Medium	High
Low	<i>Low</i>	<i>Medium</i>	<i>High</i>
Medium	<i>Medium</i>	<i>High</i>	<i>Low</i>
High	<i>High</i>	<i>Low</i>	<i>Medium</i>

The nine experiments reflect the combinations of levels listed in Table A3. To include every possible combination of levels would require 27 experiments ($3 \times 3 \times 3$).

Table A3. Combination of levels in a Latin square design for three factors with three levels each.

Experiment	Combination of levels, in sequence of Factor 1 first, then Factor 2, and finally Factor 3.
1	Low Low Low
2	Low Medium Medium
3	Low High High
4	Medium Low Medium
5	Medium Medium High
6	Medium High Low
7	High Low High
8	High Medium Low
9	High High Medium

The Greco-Latin square design is a version that accommodates four factors (of three levels each) in only nine experiments. For this example, the fourth factor is bulk density of the dry soil material. The combination of levels is listed in Table A4.

Table A4. Combination of levels in a Greco-Latin square design for four factors with three levels each. The levels associated with Factor 4 (bulk density) are in bold.

Experiment	Combination of levels, in sequence of Factor, Factor 2, Factor 3, Factor 4.
1	Low Low Low Low
2	Low Medium Medium Medium
3	Low High High High
4	Medium Low Medium Medium
5	Medium Medium High High
6	Medium High Low Low
7	High Low High High
8	High Medium Low Low
9	High High Medium Medium

That the various factors influence predicted surface temperatures is certain, since they are required by FASST (user-specified input or built-in default values). The magnitude of their influence is expected to increase with the length of a given simulation because of the cumulative effect of factor-dependent differences in heat transfer in the soil profile among simulations. Therefore, the variation in ground temperature with factor level is displayed as time series plots of the quantity $\Delta T = (T_R - T_X)$, where T_R is the surface temperature at hourly intervals predicted for the reference or standard soil, and T_X is the hourly surface temperature predicted for the experimental soil. The reference simulation is run with medium values of soil factors, with the exception of initial moisture content, for which the low value is the standard.

Appendix B. Soil Parameters for State-of-the-Ground Modeling

In military applications, the state of the ground is fundamental to troop mobility, combat engineering tasks, and battlefield sensor performance. Predictions of ground state are essential when field measurements and observations are not available and when weather-related changes in ground state must be anticipated. Implementation of state-of-the-ground models requires input values of soil parameters, yet all that may be known in advance about the soil in an area of interest is soil type. To facilitate the use of state-of-the-ground models, published measurements of soil physical, thermal, hydraulic, and optical parameters have been compiled and are presented here. The compilation primarily relies on the Department of Agriculture soil texture triangle and the Unified Soil Classification Scheme to categorize soils. Using the proposed equivalence between the textural triangle and the USCS soil categories, it is possible to make use of the extensive data sets on soil hydraulic properties based on the texture triangle and also the two major data sets of soil thermal properties based on the USCS.

The soil parameters in the compilation are saturated hydraulic conductivity, water retention parameters, density, porosity, plasticity index, albedo, emissivity, thermal conductivity, and specific heat. In addition, guidance on soil moisture content, both the amount and its distribution within a soil profile, is provided below, and a means of calculating a representative quartz content of a soil of known or assumed composition is given.

Single measurements with a specific soil have been excluded in favor of multiple measurements by soil type, so that variability among soil samples is represented in the compilation. The data sets are represented by statistics, i.e., an average value and associated standard deviation for each soil type. The statistics concisely convey the variation in soil material properties even within a single soil type, and they facilitate implementation of routines that realistically incorporate variability in soil properties within state-of-the-ground modeling.

Correspondence among USDA and USCS classifications

A difficulty with selecting suitable values of soil parameters from the compilation is that the soils are not characterized by a single classification scheme. Soil hydraulic properties are generally specified according to the U.S. Department of Agriculture Soil Textural Triangle, which designates soil types based on percentages of sand, silt, and clay (Fig. B1). Soil thermal properties typically are specified according to the Unified Soil Classification Scheme, which designates soil types on the basis of grain size (sieving), sorting (well graded vs. poorly graded), and Atterberg Limits (liquid limit, plastic limit, and shrinkage limit). These schemes reflect the different soil characteristics relevant to their primary users, i.e., soil scientists concerned with water infiltration and moisture retention versus engineers concerned with load bearing and deformation. To overcome the difficulty caused by the lack of a common classification scheme, a reasonable correspondence between the USCS and USDA soil categories has been established (Fig. B2). Non-unique soil pairings are identified in Table B1.

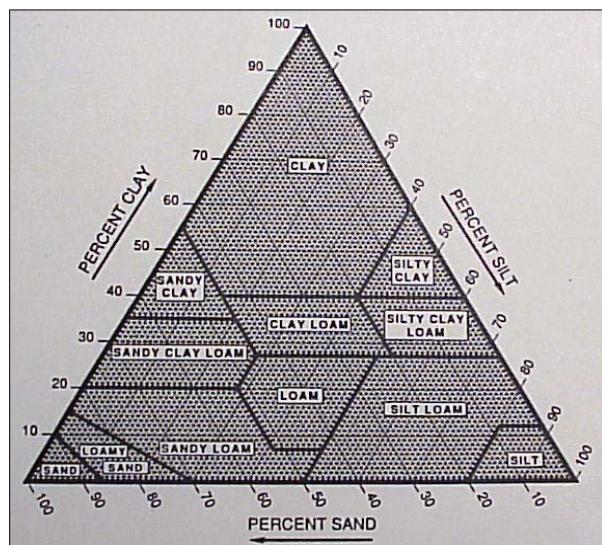


Figure B1. USDA textural triangle (Soil Survey Staff 1999). Clay particles are less than 0.002 mm in size. Silt particles are 0.002–0.05 mm. Sand particles are 0.05–2.0 mm.

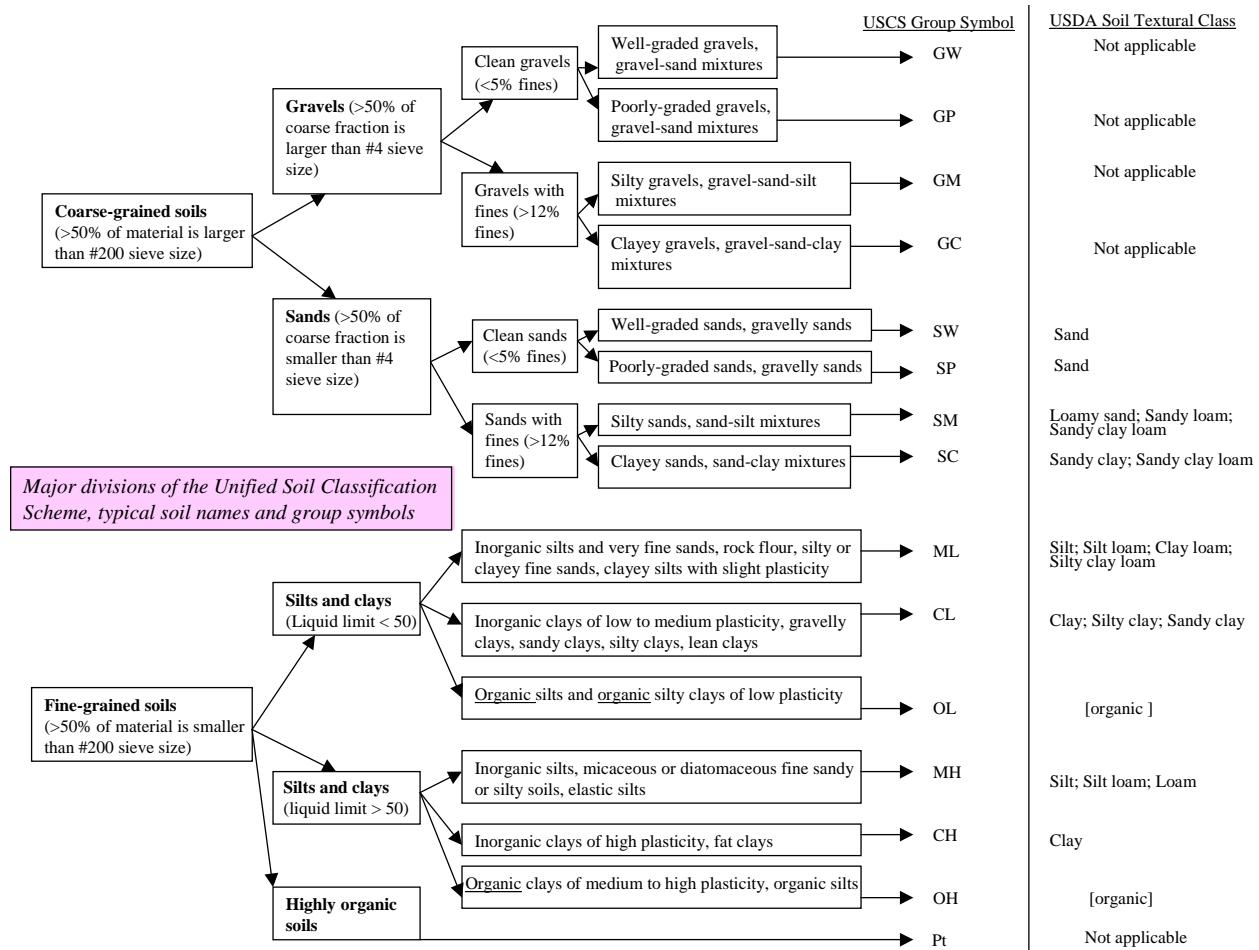


Figure B2. Proposed correspondence between USCS soil divisions and USDA soil textural classes for state-of-the-ground thermal modeling.

Table B1. Non-unique correspondence between USDA and USCS soil classifications.

USDA soil texture	USCS soil group
Sand	SW, SP
Sandy clay loam	SM, SC
Sandy clay	SC, CL
Silt	ML, MH
Silt loam	ML, MH
Clay	CL, CH

The left-hand side of Figure B2 shows major factors in soil classification according to the USCS. The division between coarse-grained and fine-grained soils is based on the percentage of material that passes a #200 sieve (0.074-mm grain size). Among coarse-grained soils, the division between gravels and sands is based on the percentage of coarse material that passes a #4 sieve (5-mm grain size). That is, of the material that did

not pass a #200 sieve, if at least 50% subsequently passes a #4 sieve, then the soil is a sand, not a gravel. Finally, sands and gravels are further subdivided by the percentage of fine material (smaller than #200 sieve) that they contain. Soils with less than 5% fines or with more than 12% fines fall in distinct categories with individual group symbols (GW, GP, SW, SP vs. GM, GC, SM, SC). Soils with 5–12% fines require two symbols to designate them.

USCS categories of fine-grained soils are based on divisions according to liquid limit, plasticity, and organic content. Liquid limit is the water content at the change between the liquid and plastic consistency states of a soil. In practice, it is the water content at which a pat of soil, cut by a standard-sized groove, will flow together for a distance of 12 mm under the impact of 25 blows in a standard liquid-limit apparatus.

The right-hand side of Figure B2 shows the proposed equivalence between USDA soil textural classes and USCS soil groups. The USDA textural classes are limited to particles of sand size or smaller, so there are no USDA counterparts to the USCS's four gravel groups (GW, GP, GM, GC). Clean sands (SW, SP) under USCS are considered equivalent to sand under USDA. Silty sands and sand-silt mixtures (SM in USCS) are associated with the lower left corner of the USDA textural triangle, which includes loamy sand, sandy loam, and sandy clay loam soils. Clayey sands and sand-clay mixtures (SC in USCS) are associated with the mid-range between sand and clay on the USDA triangle, which includes sandy clay and sandy clay loam soils. (Note that sandy clay loam is associated with both the SM and the SC groups.) The USDA textural classes do not consider a soil's organic content, so USCS soils that specifically are organic (OL, OH, Pt) do not have a counterpart in the USDA soil classes. The soils in the ML group of the USCS are associated with the lower right corner of the USDA textural triangle, which includes silt, silt loam, clay loam, and silty clay loam soils. The soils in the MH group of the USCS are associated with the low-clay-content range between silt and sand on the USDA triangle, which includes silt, silt loam, and loam soils. (Note that silt and silt loam are associated with both the ML and MH groups.) The soils in the CL group of the USCS are associated with the upper half of the USDA triangle, which includes clay, silty clay, and sandy clay soils. The soils in the CH group of the USCS are associated solely with the USDA textural class of clay. (Note that clay is associated with both the CL and CH groups.)

Moisture content estimations

A soil moisture profile for initializing state-of-the-ground models can be developed from general guidance on moisture content and moisture penetration. Soil moisture content can be estimated from Table B2, which gives the maximum and minimum volumetric moisture content (%) for various soil types in dry, moderate, and wet climates (the distinction is based on inches of rainfall per year). Columns have been added to associate the soil types with USDA and USCS soil designations in accordance with Figure B2.

Table B2. Estimates of moisture content variations for various climates and soil types. (From Miller et al. 1992.)

Soil type (USDA)	Soil type (USCS)	Soil type (Miller et al. 1992)	Volumetric Moisture Content (%)					
			Dry (<20 in./yr)		Moderate (20–80 in./yr)		Wet (>80 in./yr)	
			Min	Max	Min	Max	Min	Max
Sand	SW, SP	Clean sand	0	15	7	20	12	25
Loamy sand, Sandy loam	SM	Loamy sand	5	17	10	25	15	27
Sandy clay, Sandy clay loam	SC	Mixed clay and sand	5	17	12	27	17	30
Sandy clay	CL	Sandy clay	5	20	15	30	20	28
Clay, Silty clay, Sandy clay	CL	Lean clay	8	25	18	38	22	40
Clay	CH	Plastic clay	12	30	22	50	28	50

Moisture penetration is expressed in terms of a soil moisture control section (Soil Survey Staff 1999). The upper boundary marks how deep a dry soil would be moistened by 2.5 cm of rain in 24 hours.

The lower boundary marks how deep a dry soil would be moistened by 7.5 cm of rain in 48 hours. Table B3 indicates the location of the section boundaries for three soil groupings.

Table B3. Soil moisture control section upper and lower boundaries by soil type. (From Soil Survey Staff 1999.)

Soil particle-size class	Upper boundary (cm)	Lower boundary (cm)
Fine-loamy; coarse-silty; fine-silty; clayey	10	30
Coarse-loamy	20	60
Sandy	30	90

Hillel (1982) cited “final” (steady) infiltration rates of >20 mm/hr for sands, 10–20 mm/hr for sandy and silty soils, 5–10 mm/hr for loams, 1–5 mm/hr for clayey soils, and <1 mm/hr for sodic clayey soils. He noted that soil infiltrability is high in the early stages of infiltration, with a dependence on initial soil dryness, then tends to decrease monotonically and eventually approaches a constant rate asymptotically.

Soil hydraulic properties

There are several databases of soil hydraulic properties in which soil type follows the USDA scheme; the ones represented in Table B4 (saturated hydraulic conductivity) and Table B5 (water retention parameters) provide a statistical summary (mean and standard deviation) by soil type. The RAWLS, AHUJU, UNSODA, and ALL entries are from Schaap and Leij (1998). The RAWLS database is based on sources in the United States; 1209 samples were selected for the water retention statistical analysis (Table B5), of which 620 had measurements of saturated hydraulic conductivity (Table B4). The AHUJU database contains soils with a sandy to clay texture; 371 samples were selected for the analysis that produced the entries in Tables B4 and B5. The UNSODA database is based on international sources; 554 samples were selected for the water retention analysis, and of these, 315 yielded the saturated hydraulic conductivity statistics in Table B4. The selected samples from the RAWLS, AHUJU, and UNSODA databases were combined to create the ALL sample pool (2134 samples for water retention, of which 1306 had measured saturated hydraulic conductivity).

Hydraulic conductivity is directly proportional to the soil’s air permeability, being equal to the product of permeability, water density, and gravitational acceleration, divided by the (temperature-dependent) viscosity of water. For water at 20°C, a soil’s hydraulic conductivity is approximately 9.76×10^6 times its permeability (in SI units).

The water retention parameters (Table B5) are residual water content, saturated water content, the coefficient term “alpha,” and the power term “n,” which are independent parameters estimated from observed soil-water retention data as expressed in the form of van Genuchten’s equation. Schaap and Leij (2000) simplify the representation of water retention parameters to four soil types and a combined database (Table B6).

The van Genuchten water retention equation is

$$(\Theta - \Theta_r) / (\Theta_s - \Theta_r) = [1 + (\alpha h)^n]^{-m}$$

where Θ = volumetric soil water content at a given soil water suction, h

Θ_r = residual water content of the soil (water content of very dry soil, such that a change in water suction results in a negligible change in water content)

Θ_s = saturated water content of the soil (van Genuchten 1980).

The saturated water content cannot exceed the porosity of the soil. Leij et al. (1999) noted that the parameter α is related to the inverse of the air entry pressure, which is the pressure (or suction) at which pore water starts to drain; equivalent terms are air entry point and bubbling pressure. Of the remaining curve-fitting parameters, n has been shown to be a measure of the soil's pore size distribution, and m is assumed to be related to n by $m = 1 - n^{-1}$ (Schaap and Leij 2000).

Table B4. Saturated hydraulic conductivity by USDA soil type (1 cm/day = 0.116×10^{-6} m/s).

USDA textural class	Schaap and Leij (1998) RAWLS database			Schaap and Leij (1998) AHUJA database			Schaap and Leij (1998) UNSODA database		
	Sample size	Saturated hydraulic conductivity (cm/day)	Standard deviation (cm/day)	Sample size	Saturated hydraulic conductivity (cm/day)	Standard deviation (cm/day)	Sample size	Saturated hydraulic conductivity (cm/day)	Standard deviation (cm/day)
Sand	97	512.86	3.24	82	1023.29	2.82	74	501.19	5.50
Loamy sand	117	83.18	4.07	19	123.03	4.90	31	229.09	3.89
Sandy loam	199	33.88	4.47	65	53.70	4.37	50	41.69	5.01
Loam	32	9.77	4.27	50	6.76	8.91	31	38.02	8.32
Silty loam	61	10.96	3.47	12	17.38	2.95	62	30.20	7.24
Silt	1	26.92	na	0	na	na	2	56.23	1.58
Sandy clay loam	80	19.50	5.13	36	6.46	6.31	19	9.77	16.22
Silty clay loam	10	7.41	3.55	21	12.30	6.03	9	13.80	7.08
Clay loam	6	4.68	3.80	48	6.17	12.02	8	69.18	7.76
Sandy clay	8	21.38	2.14	2	0.93	19.05	0	na	na
Silty clay	3	6.61	3.55	5	14.13	1.45	6	8.32	5.13
Clay	6	8.71	2.04	31	10.72	6.76	23	25.70	11.22

Table B4 (cont.).

USDA textural class	Schaap and Leij (1998) ALL database		
	Sample size	Saturated hydraulic conductivity (cm/day)	Standard deviation (cm/day)
Sand	253	645.65	3.89
Loamy sand	167	104.71	4.37
Sandy loam	314	38.02	4.57
Loam	113	12.02	8.32
Silty loam	135	18.20	5.50
Silt	3	43.65	1.86
Sandy clay loam	135	13.18	7.08
Silty clay loam	40	11.22	5.75
Clay loam	62	8.13	12.30
Sandy clay	10	11.48	7.76
Silty clay	14	9.55	3.72
Clay	60	14.79	8.32

Table B5. Water retention parameters by USDA soil type ($1 \text{ cm}^3/\text{cm}^3 = 10^{-6} \text{ m}^3/10^{-6} \text{ m}^3$).

USDA textural class	Schaap and Leij (1998) RAWLS database								
	Sample size	Residual water content (cm^3/cm^3)	Residual water content, standard deviation (cm^3/cm^3)	Saturated water content (cm^3/cm^3)	Saturated water content, standard deviation (cm^3/cm^3)	$\text{Log}_{10}(\text{alpha})$	$\text{Log}_{10}(\text{alpha})$, standard deviation (cm^{-1})	$\text{Log}_{10}(n)$	$\text{Log}_{10}(n)$, standard deviation
Sand	97	0.044	0.019	0.415	0.058	-1.57	0.21	0.46	0.20
Loamy sand	135	0.040	0.037	0.395	0.074	-1.49	0.52	0.19	0.11
Sandy loam	337	0.031	0.048	0.389	0.094	-1.57	0.58	0.15	0.09
Loam	137	0.052	0.066	0.354	0.082	-2.12	0.82	0.19	0.14
Silty loam	217	0.065	0.062	0.440	0.103	-2.51	0.49	0.26	0.13
Silt	3	0.077	0.018	0.501	0.035	-2.15	0.24	0.29	0.11
Sandy clay loam	104	0.076	0.075	0.379	0.068	-1.80	0.67	0.13	0.10
Silty clay loam	47	0.110	0.064	0.46	0.057	-2.36	0.39	0.24	0.11
Clay loam	77	0.092	0.068	0.441	0.078	-1.95	0.60	0.19	0.13
Sandy clay	9	0.123	0.095	0.378	0.041	-1.40	0.60	0.09	0.06
Silty clay	12	0.071	0.101	0.467	0.051	-2.25	0.34	0.11	0.05
Clay	34	0.075	0.078	0.451	0.070	-1.93	0.47	0.11	0.06

Table B5 (cont.).

USDA textural class	Schaap and Leij (1998) AHUJA database								
	Sample size	Residual water content (cm ³ /cm ³)	Residual water content, standard deviation (cm ³ /cm ³)	Saturated water content (cm ³ /cm ³)	Saturated water content, standard deviation (cm ³ /cm ³)	Log ₁₀ (alpha) (cm ⁻¹)	Log ₁₀ (alpha), standard deviation (cm ⁻¹)	Log ₁₀ (n)	Log ₁₀ (n), standard deviation
Sand	82	0.058	0.018	0.337	0.035	-1.32	0.13	0.54	0.10
Loamy sand	19	0.054	0.041	0.339	0.043	-1.33	0.38	0.25	0.15
Sandy loam	65	0.049	0.038	0.387	0.060	-1.58	0.53	0.18	0.11
Loam	50	0.069	0.049	0.435	0.036	-2.03	0.27	0.17	0.09
Silty loam	12	0.055	0.036	0.471	0.044	-2.00	0.33	0.17	0.09
Silt	0	na	na	na	na	na	na	na	na
Sandy clay loam	36	0.039	0.063	0.378	0.037	-1.79	0.64	0.08	0.06
Silty clay loam	21	0.048	0.075	0.472	0.042	-2.05	0.39	0.10	0.05
Clay loam	48	0.060	0.075	0.428	0.045	-1.87	0.67	0.11	0.09
Sandy clay	2	0	0	0.374	0.001	-1.74	0.24	0.03	0.02
Silty clay	5	0.125	0.131	0.525	0.058	-1.23	0.69	0.12	0.08
Clay	31	0.121	0.111	0.419	0.039	-1.99	0.55	0.10	0.07

Table B5 (cont.).

USDA textural class	Schaap and Leij (1998) UNSODA database								
	Sample size	Residual water content (cm ³ /cm ³)	Residual water content, standard deviation (cm ³ /cm ³)	Saturated water content (cm ³ /cm ³)	Saturated water content, standard deviation (cm ³ /cm ³)	Log ₁₀ (alpha) (cm ⁻¹)	Log ₁₀ (alpha), standard deviation (cm ⁻¹)	Log ₁₀ (n)	Log ₁₀ (n), standard deviation
Sand	129	0.057	0.038	0.369	0.042	-1.44	0.30	0.51	0.20
Loamy sand	51	0.070	0.044	0.397	0.058	-1.43	0.29	0.37	0.19
Sandy loam	79	0.062	0.077	0.378	0.056	-1.58	0.51	0.19	0.14
Loam	62	0.074	0.098	0.469	0.111	-1.53	0.56	0.11	0.10
Silty loam	103	0.066	0.095	0.432	0.069	-1.87	0.51	0.14	0.12
Silt	3	0.023	0.033	0.476	0.093	-2.21	0.30	0.16	0.09
Sandy clay loam	41	0.053	0.088	0.400	0.055	-1.27	0.73	0.14	0.17
Silty clay loam	21	0.088	0.105	0.541	0.133	-1.47	0.65	0.14	0.17
Clay loam	25	0.077	0.093	0.470	0.115	-1.22	0.70	0.10	0.11
Sandy clay	1	0.300	na	0.473	na	-1.59	na	0.10	na
Silty clay	12	0.145	0.114	0.476	0.099	-1.56	0.50	0.13	0.13
Clay	27	0.102	0.125	0.515	0.090	-1.51	0.89	0.08	0.10

Table B5 (cont.).

USDA textural class	Schaap and Leij (1998) ALL database								
	Sample size	Residual water content (cm ³ /cm ³)	Residual water content, standard deviation (cm ³ /cm ³)	Saturated water content (cm ³ /cm ³)	Saturated water content, standard deviation (cm ³ /cm ³)	Log ₁₀ (alpha) (cm ⁻¹)	Log ₁₀ (alpha), standard deviation (cm ⁻¹)	Log ₁₀ (n) (cm ⁻¹)	Log ₁₀ (n), standard deviation
Sand	308	0.053	0.029	0.375	0.055	-1.45	0.25	0.50	0.18
Loamy sand	205	0.049	0.042	0.390	0.070	-1.46	0.47	0.24	0.16
Sandy loam	481	0.039	0.054	0.387	0.085	-1.57	0.56	0.16	0.11
Loam	249	0.061	0.073	0.399	0.098	-1.95	0.73	0.17	0.13
Silty loam	332	0.065	0.073	0.439	0.093	-2.30	0.57	0.22	0.14
Silt	6	0.050	0.041	0.489	0.078	-2.18	0.30	0.22	0.13
Sandy clay loam	181	0.063	0.078	0.384	0.061	-1.68	0.71	0.12	0.12
Silty clay loam	89	0.090	0.082	0.482	0.086	-2.08	0.59	0.18	0.13
Clay loam	150	0.079	0.076	0.442	0.079	-1.80	0.69	0.15	0.12
Sandy clay	12	0.117	0.114	0.385	0.046	-1.48	0.57	0.08	0.06
Silty clay	29	0.111	0.119	0.481	0.080	-1.79	0.64	0.12	0.10
Clay	92	0.098	0.107	0.459	0.079	-1.82	0.68	0.10	0.07

Table B6. Water retention parameters by simplified soil groupings (1 cm³/cm³ = 10⁻⁶ m³/10⁻⁶ m³). (From Schaap and Leij 2000.)

Generalized groupings	Schaap and Leij (2000) UNSODA database								
	Sample size	Residual water content (cm ³ /cm ³)	Residual water content, standard deviation (cm ³ /cm ³)	Saturated water content (cm ³ /cm ³)	Saturated water content, standard deviation (cm ³ /cm ³)	Log ₁₀ (alpha) (cm ⁻¹)	Log ₁₀ (alpha), standard deviation (cm ⁻¹)	Log ₁₀ (n) (cm ⁻¹)	Log ₁₀ (n), standard deviation
All	235	0.055	0.073	0.442	0.101	-1.66	0.52	0.214	0.209
Sands*	100	0.052	0.043	0.396	0.056	-1.58	0.37	0.349	0.228
Loams†	41	0.056	0.091	0.512	0.132	-1.39	0.5	0.076	0.047
Silts**	58	0.031	0.058	0.428	0.078	-1.92	0.52	0.139	0.141
Clays††	36	0.098	0.109	0.512	0.108	-1.75	0.64	0.114	0.112

* Sand, loamy sand, sandy loam, sandy clay loam

† Loam, clay loam

** Silty loam, silt

†† Clay, sandy clay, silty clay, silty clay loam

Soil physical properties

The soil physical properties in the compilation are density, porosity, plasticity index, and quartz content.

Soil density

Bulk density is the ratio of the mass of a soil sample (soil particles, water, and air) to the total or bulk volume of the soil sample. If there is no water in the soil sample, the bulk density is designated as dry density, equal to the mass of soil particles in a sample divided by the volume of solids and pore space. Particle density or intrinsic density is the mass per unit volume of only the soil solids. The volume fraction of solids in a soil is equal to the bulk density of the dry soil divided by the particle density of the dry soil.

Bulk Density

The means and standard deviations of bulk density of soils in the RAWLS, AHUJA, UNSODA, and ALL databases (Schaap and Leij 1998) are given in Table B7 by USDA soil type. The authors do not specify that this is a dry bulk density.

Table B7. Bulk densities of soils in the RAWLS, AHUJA, UNSODA, and ALL databases ($1 \text{ g/cm}^3 = 1000 \text{ kg/m}^3$). The number of samples by soil type for each database is the same as that listed in Table B5. (From Schaap and Leij 1998.)

USDA textural class	Schaap & Leij (1998) RAWLS database		Schaap & Leij (1998) AHUJA database		Schaap & Leij (1998) UNSODA database		Schaap & Leij (1998) ALL database	
	Bulk density (g/cm^3)	Bulk density, standard deviation (g/cm^3)	Bulk density (g/cm^3)	Bulk density, standard deviation (g/cm^3)	Bulk density (g/cm^3)	Bulk density, standard deviation (g/cm^3)	Bulk density (g/cm^3)	Bulk density, standard deviation (g/cm^3)
Sand	1.46	0.14	1.57	0.07	1.57	0.11	1.53	0.12
Loamy sand	1.51	0.20	1.63	0.08	1.51	0.15	1.52	0.19
Sandy loam	1.42	0.28	1.58	0.13	1.55	0.16	1.46	0.26
Loam	1.39	0.26	1.41	0.11	1.29	0.31	1.37	0.25
Silty loam	1.20	0.28	1.39	0.12	1.44	0.16	1.28	0.27
Silt	1.27	0.08	na	na	1.39	0.02	1.33	0.09
Sandy clay loam	1.58	0.19	1.60	0.08	1.52	0.20	1.57	0.18
Silty clay loam	1.35	0.11	1.31	0.12	1.28	0.30	1.32	0.18
Clay loam	1.41	0.15	1.48	0.15	1.36	0.30	1.42	0.19
Sandy clay	1.61	0.08	1.58	0.07	1.40	na	1.59	0.10
Silty clay	1.36	0.10	1.25	0.16	1.40	0.17	1.36	0.15
Clay	1.39	0.13	1.51	0.16	1.27	0.24	1.39	0.20

Dry density

Dry densities by USCS groupings are given in Table B8 for two sources: Salomone and Marlowe (1989) and Steinmanis (1989). The Steinmanis entries for soil samples that were repacted before density was measured are omitted from Table B8. Steinmanis includes three soil groups that are not standard to the USCS. These soil groups are: TR, coarse-grained glacial till (no clay; well graded to cobble size); TF, fine-grained glacial till (some clay; well graded to gravel size); and CI, intermediate plastic clays.

Particle density

The dry particle density of soil can be estimated in accordance with the observations of Brady (1974) that 1) the particle density of most mineral solids is in the range 2600–2750 kg/m³, 2) the particle density of mineral topsoils high in organic matter may drop to 2400 kg/m³ or less, and 3) for general calculations, an average arable surface soil may be considered to have a particle density of approximately 2650 kg/m³.

Table B8. Dry density (kg/m³) of soils by USCS soil group (1 kg/m³ = 1 × 10⁻³ g/cm³).

USCS Soil Group	Steinmanis (1989)				Salomone and Marlowe (1989)			
	Average	Standard deviation	Range	Number of samples	Average	Standard deviation	Range	Number of samples
GW								
GP					1400			1
GM								
GC								
SW					1770	77	1650–1880	8
SP	1660	130	1390–1880	12	1540	193	1050–1790	15
SM	1600	70	1530–1730	8	1750	259	1280–2120	17
SC					1560	160	1200–1660	7
ML	1530	160	1310–1860	12	1690	132	1520–1950	12
CL	1680	210	1270–1980		1610	106	1530–1680	2
OL	970	100	900–1040	2	1290	85	1230–1350	2
MH								
CH	1370	200	1100–1600	5	1500			1
OH	910	290	700–1110	2	860	313	480–1200	6
Pt	220			1	250			1
TR	1890	40	1850–1930	3				
TF	1940	90	1790–2040	8				
CI	1560	180	1310–1930	11				

Porosity

The porosity of a soil is the ratio of the volume of voids of a given soil mass to the total volume of the soil mass. Porosity is equivalent to the quantity one minus the soil's volume fraction. The water content of a soil cannot exceed its porosity. Porosity information by USDA soil type is presented in two forms in Table B9: total porosity and effective porosity. The latter is equal to total porosity minus residual saturation.

Table B9. Total and effective soil porosity, by USDA soil type ($1 \text{ cm}^3/\text{cm}^3 = 10^{-6} \text{ m}^3/10^{-6} \text{ m}^3$). (From Rawls et al. 1992.)

USDA textural class	Total porosity, mean (cm^3/cm^3)	Total porosity, standard deviation (cm^3/cm^3)	Effective porosity, mean (cm^3/cm^3)	Effective porosity, standard deviation (cm^3/cm^3)
Sand	0.437	0.063	0.417	0.063
Loamy sand	0.437	0.069	0.401	0.072
Sandy loam	0.453	0.102	0.412	0.129
Loam	0.463	0.088	0.434	0.1
Silty loam	0.501	0.081	0.486	0.092
Silt				
Sandy clay loam	0.398	0.066	0.33	0.095
Silty clay loam	0.471	0.053	0.432	0.085
Clay loam	0.464	0.055	0.39	0.111
Sandy clay	0.43	0.06	0.321	0.114
Silty clay	0.479	0.054	0.423	0.089
Clay	0.475	0.048	0.385	0.116

Plasticity index

The plasticity index is defined as the numerical difference between the liquid limit and the plastic limit of a soil; it is the range of moisture content within which the soil remains plastic. A soil's plastic limit is the moisture content at which a soil changes from semisolid to plastic. Its liquid limit is the moisture content at which the soil passes from a plastic to a liquid state. In practical terms, a clayey soil (clay, clay loam, or silt clay loam) should have a non-zero plasticity index, although the presence of rock fragments can cause even a clayey soil's plasticity index to be zero. A zero plasticity index is increasingly likely as a soil's sand content increases and its clay content decreases.

The plasticity index values presented in Table B10 were extracted from the State Soil Geographic (STATSGO) soils database compiled by the Natural

Resources Conservation Service of the U.S. Department of Agriculture. Soil properties within STATSGO are reported for eleven standard soil layers from the soil surface (0 cm) to a depth of 250 cm; layer thickness ranges from 5 cm near the surface to 50 cm for the deepest (eleventh) layer. To develop a reference table of soil plasticity index as a function of soil type and depth, the STATSGO database for Texas was queried for all plasticity index entries, together with their associated depth and USCS soil type. This selection of standard layer data was then sorted first by soil type and second by depth to obtain groupings of plasticity index for a given soil type within each standard layer. The maximum, minimum, and average plasticity indexes for each grouping were then determined. Note that this process mixed values from many different physical soil layers and map units within Texas. The process was repeated for soils in Alabama, Arizona, Georgia, Louisiana, Maryland, Mississippi, Oklahoma, Oregon, South Carolina, Tennessee, and Virginia to obtain a plasticity profile for silt, which was lacking from the STATSGO database for Texas.

Table B10. Plasticity index of USDA soil types based on STATSGO data for Texas.

Soil	Depth (cm)	Average	Standard deviation	Maximum	Minimum	Number of samples
C (Clay)	0-5	30.9	6.9	46	16	91
	5-10	30.9	6.9	46	16	91
	10-20	31.1	6.7	47	17	102
	20-30	30.1	7.4	48	15	170
	30-40	29.5	8.0	52	13	185
	40-60	29.3	8.3	52	11	189
	60-80	30.1	8.0	52	13	178
	80-100	30.5	8.2	52	13	153
CL (Clay loam)	0-5	20.3	5.2	32	10	94
	5-10	20.3	5.2	32	10	93
	10-20	20.4	5.2	32	10	85
	20-30	21.1	4.4	31	11	53
	30-40	20.9	4.5	31	11	52
	40-60	22.1	5.0	34	10	43
	60-80	22.0	5.8	34	10	50
	80-100	21.4	6.5	39	9	67

Table B10 (cont.).

L (Loam)	0-5	12.6	4.2	24	3	95
	5-10	12.6	4.2	24	3	95
	10-20	13.0	4.3	24	3	91
	20-30	14.7	4.6	26	7	71
	30-40	14.9	5.2	28	4	58
	40-60	16.1	4.6	29	9	62
	60-80	17.3	4.7	30	9	71
	80-100	16.5	5.0	31	7	59
LS (Loamy sand)	0-5	2.4	1.3	4	1	7
	5-10	2.6	1.3	4	1	7
	10-20	2.6	1.0	4	1	7
	20-30	3.9	2.0	8	2	7
	30-40	4.9	3.6	12	2	7
	40-60	5.6	4.1	14	2	7
	60-80	6.1	4.2	15	2	8
	80-100	6.6	4.6	16	2	7
S (Sand)	0-5	3.2	2.0	12	0	88
	5-10	3.2	2.0	12	0	88
	10-20	3.4	2.2	12	0	86
	20-30	4.8	3.6	18	1	83
	30-40	5.6	3.9	17	1	74
	40-60	6.4	4.7	20	1	58
	60-80	7.1	4.8	16	1	49
	80-100	5.8	4.2	14	1	30
SC (Sandy clay)	0-5	†	†	†	†	†
	5-10	†	†	†	†	†
	10-20	†	†	†	†	†
	20-30	23.3	5.1	30	18	4
	30-40	22.7	3.8	31	17	12
	40-60	24.8	4.8	35	17	16
	60-80	24.1	5.6	35	15	11
	80-100	21.4	5.6	35	14	14

Table B10 (cont.).

SCL (Sandy clay loam)	0-5	15.6	3.2	23	11	16
	5-10	15.8	3.4	24	11	16
	10-20	16.8	3.9	26	8	21
	20-30	16.2	5.0	28	7	37
	30-40	16.3	4.8	30	8	62
	40-60	16.2	5.4	29	8	83
	60-80	16.2	5.3	29	5	96
	80-100	16.9	6.1	33	5	108
SI (Silt)*	0-5	2	NA	NA	NA	1
	5-10	2	NA	NA	NA	1
	10-20	5.3	2.9	7	2	3
	20-30	7.3	3.4	14	2	9
	30-40	7.6	3.7	14	2	9
	40-60	8.1	3.9	15	2	9
	60-80	7.9	3.5	13	2	9
	80-100	7.4	2.9	11	2	9
SIC (Silty clay)	0-5	29.9	6.3	42	18	17
	5-10	29.9	6.3	42	18	17
	10-20	30.4	5.5	43	22	20
	20-30	30.6	5.7	43	21	21
	30-40	28.4	6.4	46	16	24
	40-60	26.1	6.7	40	15	18
	60-80	24.3	6.9	38	14	15
	80-100	23.4	6.6	37	14	13
SICL (Silty clay loam)	0-5	22.7	4.2	33	14	25
	5-10	22.2	4.4	33	14	27
	10-20	22.8	4.7	35	14	25
	20-30	25.1	5.9	37	14	17
	30-40	21.5	8.2	34	10	12
	40-60	20.8	7.6	33	9	11
	60-80	21.3	7.1	33	8	14
	80-100	21.4	8.3	37	7	14

Table B10 (cont.).

SIL (Silt loam)	0-5	11.3	4.6	23	3	23
	5-10	11.3	4.7	23	3	22
	10-20	11.6	4.2	20	4	16
	20-30	11.7	4.1	18	4	15
	30-40	13.3	4.7	20	5	12
	40-60	14.0	6.3	24	5	9
	60-80	13.1	4.7	19	5	7
	80-100	13.0	4.2	18	6	6
SL (Sandy loam)	0-5	7.1	3.8	22	2	173
	5-10	7.1	3.8	22	2	173
	10-20	8.3	4.4	24	2	173
	20-30	10.2	4.7	24	3	118
	30-40	10.3	4.8	24	3	70
	40-60	9.8	4.8	24	3	44
	60-80	10.1	4.8	24	4	43
	80-100	10.7	4.9	24	4	44

* Plasticity profile of silt based on STATSGO data for Alabama, Arizona, Georgia, Louisiana, Maryland, Mississippi, North Carolina, Oklahoma, Oregon, South Carolina, Tennessee, and Virginia.

† No data.

Quartz content

When the mineral composition is not reported for a soil, the procedure described here can be used to obtain an approximate quartz content of a soil based on its texture. Tarnawski et al. (1997) proposed that the quartz content of a soil can be calculated from the mass fraction of clay, silt, sand, and gravel in a soil according to:

$$\text{Quartz content} = 0.05 \times M_{\text{Clay}} + 0.35 \times M_{\text{Silt}} + 0.80 \times M_{\text{Sand}} + 0.65 \times M_{\text{Gravel}}$$

where M_{xxx} is the mass fraction of each of the four soil components. For cases where the specific composition of a soil is unknown, Tarnawski et al (1997) provided a representative composition of each of the USDA soil textures. Substituting the representative mass fractions of clay, silt, sand, and gravel in the above equation results in the values of quartz content by soil type presented in Table B11.

Table B11. Calculated quartz content (mass fraction) of USDA soil types based on Tarnawski et al. (1997).

Soil texture	Quartz content
Sand	0.75
Loamy sand	0.70
Sandy loam	0.62
Loam	0.51
Silty loam	0.40
Silt	0.36
Sandy clay loam	0.49
Clay loam	0.40
Silty clay loam	0.30
Sandy clay	0.37
Silty clay	0.21
Clay	0.21

Soil Optical Properties

Albedo

The albedo of a soil is the ratio of reflected solar radiation to incident solar radiation at the soil surface. Compilations of soil albedo by USDA or USCS soil type were not found, presumably because albedo depends on soil moisture content and soil color, which are not uniquely distributed among the soil types. Typical soil albedos used by Wilson (1984) are given in Table B12; they are applicable when modeling bare soil scenarios. If the ground is partially or fully vegetated, then the albedo of the appropriate land type component (tree, forest, woodland, shrub, grass, or crop), such as from Wilson's seasonal and annual lists, must be incorporated in the modeling. As a comparison with Table B12, Oke (1983) cited the albedo of soil as ranging from 0.05 for dark, wet soils to 0.40 for light, dry soils.

Table B12. Typical soil albedos. (From Wilson 1984, Table 4.15.)

Soil color class	Light		Medium		Dark	
	Wet	Dry	Wet	Dry	Wet	Dry
Albedo	0.18	0.35	0.10	0.20	0.07	0.15
Average	0.26		0.15		0.11	

Emissivity

The emissivity of a material is the ratio of the energy the material emits at a given temperature to the energy it would emit if it were a black body. No compilation of soil emissivity by USDA or USCS type was found. Specifying the emissivity of a given soil type in modeling the state of the ground is further complicated because emissivity depends on wavelength. One source of soil emissivity measurements over the spectral range 3.34–15.15 microns is the Moderate Resolution Imaging Spectrometer (MODIS) Emissivity Library of the University of California, Santa Barbara (<http://www.ices.ucs.edu/modis/EMIS/html/em.html>). The MODIS database does not include characterization of the soil samples. A sample plot is given in Figure B3 for soil samples from Nebraska. The database is chiefly useful for conveying the variability in soil emissivity, such that high and low approximate emissivities can be used in state-of-the-ground simulations to determine the uncertainty in calculated soil temperatures arising from any error in specified emissivity.

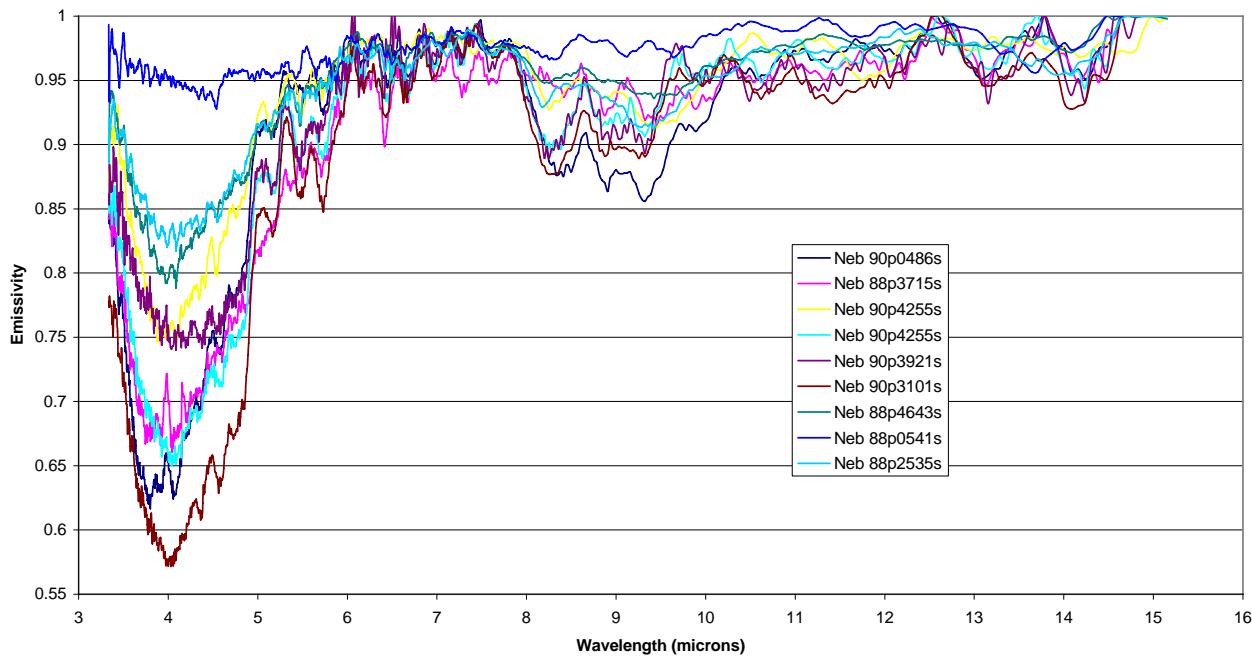


Figure B3. Measured emissivity of Nebraska soil samples from the MODIS UCSB Emissivity Library.

Garratt (1992) presented values of emissivity for two soil types (sandy and clay) that are wet or dry (Table B13). These emissivity values suggest that the emissivity of sandy soil can be slightly higher than that of clay and that both for sandy soil and clay, emissivity is higher when the soil is wet. Garratt refers to the 0.9 emissivity of dry, sandy soil as low. The effect on predicted soil surface temperatures of differences in emissivity of this

magnitude (0.98 vs. 0.95) will be known after completion of sensitivity studies.

Table B13. Representative values of longwave emissivity of soils. (From Garratt 1992, Table A8.)

Soil	Emissivity
Wet sandy	0.98
Wet clay	0.97
Dry sandy	0.9–0.95
Dry clay	0.95

Soil Thermal Properties

A soil's mineralogy, porosity, and moisture content influence its thermal properties because each of its constituents (solids, air, and water) has inherently different thermal conductivities and specific heats (or heat capacities). Temperature affects soil thermal properties through the pore water being liquid or ice; the thermal conductivity of water increases from 0.57 W/m·°C at 4°C to 2.24 W/m·°C as ice at 0°C (Oke 1993). Examples of the variation in soil thermal conductivity with soil type, moisture content, and frozen/unfrozen state are given in Table B14; Peck and O'Neill (1997) used these values in simulating frost penetration in soil. Typically, a soil's thermal conductivity increases when the soil freezes. At low moisture content, however, such as the sand in Table B14, the higher thermal conductivity of ice may be offset by decreased heat conduction at contact points between soil particles when water at the contact points is removed to form ice in the soil pores (Farouki 1981). Since the thermal conductivity of air is approximately 1/20th that of unfrozen water, the loss of water from contact points causes the thermal conductivity of frozen soil of low moisture content to be less than it is when the soil is not frozen.

Table B14. Variation in soil thermal conductivity with soil type, moisture content, and frozen/unfrozen state. (After Peck and O'Neill 1997, Table 1.)

Soil	Volumetric unfrozen moisture content (10^{-6} m ³ water / 10^{-6} m ³ soil)	Thermal conductivity (W/m·°C)	
		Unfrozen	Frozen
Silty soil	0.15	0.80	0.81
	0.25	1.04	1.27
	0.37	1.21	1.73
Sand	0.05	0.75	0.63

Soil thermal properties typically are expressed in terms of the USCS soil groups. Steinmanis (1989) presented the results of testing 100 soil samples from across Canada; Salomone and Marlowe (1989) also incorporated a large number of soil groups from wide geographic sampling. Selecting thermal properties from these two sources ensures that realistic variation in soil thermal properties is represented for each soil group. As noted above, however, for state-of-the-ground applications involving frozen soil, thermal conductivities and also specific heats appropriate for frozen soil must be used in characterizing a soil.

Thermal Conductivity

Thermal conductivity is the heat flow per unit time per unit temperature gradient across a cross-sectional area of material ($J/s \cdot cm \cdot ^\circ C = 10^2 \text{ W/m} \cdot ^\circ C$); the transfer of heat occurs by conduction. Steinmanis (1989) and Salomone and Marlowe (1989) presented their data as thermal dryout curves, i.e., thermal resistivity as a function of soil moisture content (% dry weight), where thermal resistivity is the inverse of thermal conductivity. Steinmanis summarized his data in figures showing the envelope of thermal dryout curves for a given USCS soil group. For this compilation, the upper and lower bounds of his envelopes were converted to thermal conductivity as a function of moisture content, and fitted with curves as given in Table B15, together with the maximum moisture content for which a measurement of thermal resistivity was made. The curves are valid for moisture contents greater than 0 wt. % ($x \geq 1$ in Table B5 equations). If the soil moisture content changes during a simulation because of water migration, infiltration, or evaporation, then the soil's thermal conductivity must be recalculated.

Steinmanis used a modified USCS, having three soil groups (TR, TF, and CI) that are not standard in the USCS. These soil groups are TR, coarse-grained glacial till (no clay; well graded to cobble size); TF, fine-grained glacial till (some clay; well graded to gravel size); and CI, intermediate plastic clays.

Salomone and Marlowe (1989) presented a thermal dryout curve for each soil sample. The equations of logarithmic curves fit to the thermal dryout curves (converted to thermal conductivity) are given in Table B16. Soil descriptions are given in Table B17, together with the range in moisture content that defines the thermal dryout curves and, where applicable, the sample's dry thermal conductivity (thermal conductivity at 0% moisture content).

Table B15. Equations for thermal conductivity by USCS soil group, as a function of moisture content, based on plots in Steinmanis (1989).

USCS soil group	Upper bound (W/m·°C)	Lower bound (W/m·°C)	R ² (upper bound, lower bound)	Maximum moisture content (% dry weight)
GW				
GP				
GM				
GC				
SW				
SP (combined with SM)	$Y = 0.468\ln(x) + 0.749$	$Y = 0.443\ln(x) + 0.180$	0.995, 0.965	20
SM (combined with SP)	$Y = 0.468\ln(x) + 0.749$	$Y = 0.443\ln(x) + 0.180$	0.995, 0.965	20
SC				
ML	$Y = 0.428\ln(x) + 0.437$	$Y = 0.281\ln(x) + 0.307$	0.959, 0.947	20
CL (combined with CL)	$Y = 0.367\ln(x) + 0.610$	$Y = 0.281\ln(x) + 0.325$	0.969, 0.920	25
OL (combined with OH)	$Y = 0.194\ln(x) + 0.196$	$Y = 0.230\ln(x) - 0.108$	0.895, 0.987	30
MH				
CH	$Y = 0.281\ln(x) + 0.325$	$Y = 0.215\ln(x) + 0.265$	0.920, 0.910	25
OH (combined with OL)	$Y = 0.194\ln(x) + 0.196$	$Y = 0.230\ln(x) - 0.108$	0.895, 0.987	
Pt				
TR	$Y = 0.625\ln(x) + 1.607$	$Y = 0.484\ln(x) + 0.657$	0.988, 0.988	10
TF	$Y = 0.496\ln(x) + 1.320$	$Y = 0.372\ln(x) + 0.885$	0.985, 0.973	10
CL (combined with CL)	$Y = 0.367\ln(x) + 0.610$	$Y = 0.281\ln(x) + 0.325$	0.969, 0.920	25

Table B16. Equations for thermal conductivity by USCS soil group, as a function of moisture content, based on plots in Salomone and Marlowe (1989). Thermal conductivity (Y) has units of W/m·°C. Moisture content (x) is given as percent dry weight of the soil, i.e., the mass of water in the soil sample divided by the mass of the soil sample when dry, expressed as a percentage.

USCS soil group	Sample (figure number)	Thermal conductivity equation (W/m·°C)	R ²
GW			
GP	A-24	$Y = 0.392\ln(x) + 0.211$	0.901
GM			
GC			
SW	A-4	$Y = 0.840\ln(x) + 0.540$	0.963
	A-12	$Y = 1.350\ln(x) - 0.037$	0.970
	A-30	$Y = 0.749\ln(x) + 0.563$	0.988
	A-31	$Y = 0.559\ln(x) + 0.310$	0.983
	A-32	$Y = 0.516\ln(x) + 0.337$	0.960
	A-33	$Y = 0.653\ln(x) + 0.202$	0.990
	A-36	$Y = 0.792\ln(x) + 0.020$	0.999
	A-44	$Y = 0.248\ln(x) + 0.301$	0.989

Table B16 (cont.).

SP	A-9	$Y = 0.599\ln(x) + 0.355$	0.966
	A-15	$Y = 0.596\ln(x) + 0.161$	0.913
	A-19	$Y = 0.626\ln(x) + 0.029$	0.970
	A-20	$Y = 1.178\ln(x) + 0.030$	0.985
	A-21	$Y = 1.102\ln(x) + 0.012$	0.997
	A-23	$Y = 0.623\ln(x) - 0.167$	0.875
	A-26	$Y = 0.889\ln(x) + 0.970$	0.995
	A-27	$Y = 0.591\ln(x) + 0.817$	0.992
	A-28	$Y = 0.806\ln(x) + 0.734$	0.992
	A-29	$Y = 0.738\ln(x) + 0.639$	0.983
	A-46	$Y = 0.415\ln(x) + 0.357$	0.972
	A-48	$Y = 0.422\ln(x) + 0.419$	0.961
	A-50	$Y = 1.286\ln(x) - 0.447$	0.974
	A-51	$Y = 1.082\ln(x) - 0.349$	0.969
	A-52	$Y = 0.947\ln(x) - 0.358$	0.956
SM	A-3	$Y = 1.204\ln(x) + 0.160$	0.964
	A-5	$Y = 1.409\ln(x) + 0.142$	0.979
	A-6	$Y = 1.234\ln(x) + 0.377$	0.988
	A-7	$Y = 1.277\ln(x) - 0.158$	0.973
	A-8	$Y = 0.813\ln(x) + 0.301$	0.989
	A-11	$Y = 1.039\ln(x) + 0.335$	0.997
	A-13	$Y = 0.641\ln(x) + 0.822$	0.975
	A-16	$Y = 0.518\ln(x) + 0.194$	0.939
	A-17	$Y = 0.277\ln(x) + 0.557$	0.999
	A-18	$Y = 0.418\ln(x) + 0.447$	0.977
	A-22	$Y = 0.827\ln(9x) + 0.453$	0.982
	A-25	$Y = 0.339\ln(x) + 0.235$	0.946
	A-41	$Y = 0.652\ln(x) - 0.152$	0.873
	A-47	$Y = 0.501\ln(x) + 0.099$	0.971
	A-53	$Y = 0.264\ln(x) + 0.057$	0.779
	A-68	$Y = 0.628\ln(x) - 0.497$	0.970
	A-69	$Y = 0.448\ln(x) - 0.297$	0.936
SC	A-40	$Y = 0.567\ln(x) - 0.077$	0.872
	A-42	$Y = 0.401\ln(x) + 0.072$	0.946
	A-59	$Y = 1.063\ln(x) - 1.208$	0.873
	A-60	$Y = 0.326\ln(x) + 0.234$	0.884
	A-62	$Y = 0.294\ln(x) + 0.247$	0.860
	A-63	$Y = 0.755\ln(x) - 0.476$	0.988
	A-64	$Y = 0.338\ln(x) + 0.132$	0.800

Table B16 (cont.).

ML	A-14	$Y = 1.297\ln(x) + 0.172$	0.993
	A-34	$Y = 0.650\ln(x) + 0.007$	0.990
	A-35	$Y = 0.670\ln(x) + 0.056$	0.952
	A-37	$Y = 0.491\ln(x) + 0.125$	0.981
	A-38	$Y = 0.706\ln(x) - 0.192$	0.039
	A-43	$Y = 0.374\ln(x) + 0.151$	0.899
	A-45	$Y = 0.485\ln(x) + 0.515$	0.883
	A-49	$Y = 0.495\ln(x) + 0.101$	0.972
	A-54	$Y = 0.401\ln(x) + 0.019$	0.975
	A-57	$Y = 0.586\ln(x) + 0.565$	0.829
	A-58	$Y = 0.681\ln(x) - 0.081$	0.959
	A-67	$Y = 0.327\ln(x) + 0.108$	0.921
CL	A-39	$Y = 0.647\ln(x) - 0.146$	0.927
	A-61	$Y = 0.611\ln(x) - 0.063$	0.928
OL	A-55	$Y = 0.306\ln(x) - 0.012$	0.839
	A-56	$Y = 0.247\ln(x) + 0.034$	0.891
MH			
CH	A-65	$Y = 0.512\ln(x) - 0.242$	0.957
OH	A-70	$Y = 0.211\ln(x) - 0.037$	0.855
	A-71	$Y = 0.243\ln(x) - 0.146$	0.898
	A-72	$Y = 0.323\ln(x) - 0.280$	0.920
	A-73	$Y = 0.230\ln(x) - 0.172$	0.862
	A-74	$Y = 0.314\ln(x) - 0.486$	0.970
	A-75	$Y = 0.294\ln(x) - 0.500$	0.931
Pt	A-78	$Y = 0.215\ln(x) - 0.669$	0.990

Table B17. Soils samples in the database of Salomone and Marlowe (1989) ($1 \text{ g/cm}^3 = 1000 \text{ kg/m}^3$).

USCS	Sample (figure number)	Description	Dry density (g/cm^3)	Moisture content range (% dry weight)	Thermal conductivity at 0% moisture ($\text{W/m} \cdot \text{°C}$)
GP	A-24	Black fine to coarse gravel-size cinders with fine to coarse gravelly sand	1.40	0-12	0.44
SW	A-4	Red-brown gravelly sand with some silt	1.80	0-8	0.88
	A-12	Fine to coarse sand with fine to medium gravel	1.86	~1-10	
	A-30	Light gray fine to coarse sand with trace silt and some fine gravel	1.88	~0-12	0.35
**	A-36	Light gray fine to coarse sand with trace silt and some fine gravel	1.75	0-12	0.30
	A-31	Fine to medium sand	1.75	0-8	0.36
	A-32	Medium to coarse sand	1.65	0-8	0.32
	A-33	Fine to coarse sand	1.76	0-10	0.33

Table B17 (cont.).

	A-44	Compact moist brown and black fine sand to coarse gravel and slag fill	1.70	0-12	0.36
SP	A-9	Light brown calcareous gravelly sand with some silt	1.05	0-12	0.54
	A-15	Light gray-brown gravelly sand with trace silt, ash, organic	1.25	~1-12	
	A-19	Red-brown sandy silt with fine to coarse gravel	1.70	~1-14	
	A-20	Gray rounded fine to coarse sand with fine gravel	1.73	~0-6	0.43
	A-21	Brown fine to coarse sand with fine to medium gravel	1.79	0-10	0.41
	A-23	Brown silty granular fill	1.64	0-16	0.42
	A-26	Yellow fine sand	1.67	0-8	0.34
	A-27	Fine silica sand	1.62	0-9	0.32
	A-28	Fine silica sand	1.62	0-9	0.32
	A-29	White fine sand	1.60	0-9	0.30
	A-46	Fine to medium beach sand	1.50	0-16	0.29
	A-48	Fine to medium sand	1.60	0-16	0.26
	A-50	White sand with some root and organics	1.49	0-8	0.25
	A-51	Yellow sand with fine decomposed organics	1.49	~0-9	
	A-52	Very soft gray organic sandy silt, shell fragments and some clay	1.40	0-12	0.25
SM	A-3	Light gray-brown fine sandy silt with some fine to coarse rounded gravel	1.94	0-12	0.83
	A-5	Crushed limestone screenings	2.12	0-10	0.76
**	A-11	Crushed limestone screenings	1.83	0-8	0.51
	A-6	Fine to coarse granular fill	2.07	0-9	0.63
	A-7	Red-brown sandy silt with fine to coarse gravel	2.00	0-10	0.63
	A-8	Crushed stone	2.02	0-10	0.65
**	A-17	Crushed stone	1.82	0-8	0.51
	A-13	Crushed shale and limestone screenings	1.76	0-8	
	A-16	Red-brown fine silty sand with fine to medium gravel	1.89	~0-10	
	A-18	Gray-brown fine sandy silt with fine to coarse gravel, some cinders	1.35	~1-16	
	A-22	Fine to coarse sand with some silt and trace gravel	1.73	0-8	0.39
	A-25	Red-brown silty sand with some gravel	1.80	0-12	0.43
	A-41	Fine to medium sand, some silt, trace gravel	1.62	0-16	0.33
	A-47	Silty very fine sand	1.62	0-10	0.29
	A-53	Red-brown fine to medium sand with some gravel and silt	1.65	0-12	0.29

Table B17 (cont.).

	A-68	Black organic sandy silty fill	1.30	~1-30	
	A-69	Dark brown organic sandy silt with some fine to coarse gravel	1.28	~1-20	
SC	A-40	Red-brown very silty clay till with a trace of fine gravel	1.63	0-15	0.34
	A-42	Gravel, sand, and clay fill	1.58	0-16	0.35
	A-59	Gray-brown clayey sandy silt with some fine gravel and shell fragments	1.20	0-24	0.40
	A-60	Light brown silty clay till with trace gravel	1.66	0-24	0.39
	A-62	Brown silty clay till with trace gravel	1.58	0-22	0.37
	A-63	Light brown clayey silt with some gravel	1.63	0-30	0.31
	A-64	Brown silty clay till with trace fine gravel	1.62	0-25	0.34
ML	A-14	Red very fine sandy silt	1.95	~0-9	
	A-34	Light gray-brown silt with some gravel and organics	1.62	0-14	0.32
	A-35	Dark gray-brown slightly clayey silt with trace sand	1.52	0-18	0.31
	A-37	Stiff brown moist silt till with some clay and trace sand	1.80	0-15	0.37
	A-38	Organic sand with silt	1.63	0-16	0.33
	A-43	Hard moist gray silty clay till with little sand and fine gravel	1.77	0-~18	0.36
	A-45	Fine silty sand	1.75	0-8	0.30
	A-49	Sandy silt	1.82	0-10	0.27
	A-54	Silt with very fine sand	1.52	0-15	0.25
	A-57	Gray-brown micaceous silty fine sand with trace fine gravel and shell fragments	1.65	0-22	0.30
	A-58	Red-brown clayey silt with some gravel	1.63	0-~34	0.34
	A-67	Stiff moist gray-brown clayey silt with trace sand and organics	1.57	0-26	0.26
CL	A-39	Soft to firm moist gray-brown silty clay with trace fine sand and organics	1.68	0-18	0.35
	A-61	Gray-brown silty clay	1.53	0-24	0.36
OL	A-55	Very soft dark gray-green silty clayey organic sediment with some fine shell fragments	1.35	~0-16	
	A-56	Firm blue-gray organic clayey silt in shell fragment matrix	1.23	~1-15	
CH	A-65	Blue clay	1.50	0-32	0.29
OH	A-70	Extremely soft dark green silty clayey organic sediment with fine shell fragments	1.14	0-~35	0.25
	A-71	Organic clayey silt	0.60	~2-~35	
	A-72	Very soft blue-gray organic clayey silt sediment	1.20	0-~40	0.20
	A-73	Very soft dark gray organic clayey silt	1.06	0-~40	0.20

Table B17 (cont.).

	A-74	Highly organic gray, very silty micaceous clay with trace shell fragments	0.65	0-~68	0.17
	A-75	Highly organic gray, very silty clay with many shell fragments	0.48	~3-68	
Pt	A-78	Dark brown to black highly decomposed woody peat (Radforth = BEI)	0.25	~30-~350	

Specific heat

Specific heat is the quantity of heat required to increase the temperature of a unit mass of material 1°C. The averages, standard deviations, and ranges of the specific heat of soil by USCS groups are given in Table B18. These values were obtained with soil samples that are represented in Steinmanis's thermal conductivity data of Table B15 and dry density data of Table B8. Steinmanis reported average specific heats but excluded OH and OL; average values for these soil groups were calculated for this compilation. The ranges and standard deviations are based on individual measurement values that were extracted from Steinmanis's Appendix A. Steinmanis noted that even with nominal amounts of organics the specific heats range only from approximately 0.190 (generally sandy) to approximately 0.210 (generally clayey) cal/gm-°C, so a value of 0.20 cal/gm-°C (837 J/kg-°C) for most soils should be suitable unless a soil is very organic.

Steinmanis uses a modified USCS, having three soil groups (TR, TF, and CI) that are not standard in the USCS. These soil groups are TR, coarse-grained glacial till (no clay; well graded to cobble size); TF, fine-grained glacial till (some clay; well graded to gravel size); and CI, intermediate plastic clays.

For certain soil groups the average value reported by Steinmanis disagrees with the average value calculated from the individual values given in his Appendix A. For those cases, Steinmanis's value is in brackets. The standard deviations and ranges shown for all soil groups correspond to the averages calculated from his Appendix A data.

Table B18. Specific heat of soils by USCS groups. (Based on Steinmanis 1989.)

USCS soil group	Specific heat (J/kg·°C)			Number of samples
	Average	Standard deviation	Range	
GW				
GP				
GM				
GC				
SW				
SP	816.4	8.4	803.9–833.2	17
SM	820.6	8.4	808.1–824.8	10
SC				
ML	845.7 [841.5]	20.9	808.1–875.0	16
CL	854.1	12.6	837.4–875.0	7
OL	837.4	12.6	829.0–845.7	2
MH				
CH	845.7 [870.9]	37.7	803.9–887.6	5
OH	866.7	54.4	824.8–904.3	2
Pt				
TR	849.9	20.9	803.9–879.2	15
TF	858.3	12.6	833.2–887.6	15
CI	849.9 [854.1]	16.7	824.8–870.9	11

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14. ABSTRACT This report presents the results of a systematic investigation of the variation in soil surface temperatures predicted by the numerical model FASST (Fast All Seasons Soil Strength), using different values of soil physical, thermal, and optical parameters. Soil hydraulic properties were not varied. Single-factor experiments have shown that the major soil parameters for FASST predictions are, in descending order, initial volumetric soil moisture content, bulk density of the dry soil material, albedo (sunny days), and porosity. The thermal conductivity of the dry soil material has a minor effect on predicted soil temperature. Quartz content, specific heat of the dry soil material, and emissivity each has a negligible effect on predicted soil temperature. Experiments varying several soil parameters simultaneously produced temperature differences (relative to a standard soil) for some combinations of factors that are larger than were obtained by varying a single major soil factor. This highlights the difficulty of associating a measure of confidence with a given FASST simulation, i.e., how closely predicted temperatures will match actual soil temperatures for a given soil type and weather scenario, given that the predicted temperature depends on the cumulative effect of the accuracy of the value assigned to each of the significant soil parameters.					
15. SUBJECT TERMS FASST Soil temperature					
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